THE UNIVERSITY OF ALBERTA

THE ULTIMATE LOAD CAPACITY OF STEEL FRAMES

A THESIS

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SYNOPSIS

Results of tests to determine the ultimate load carrying capacity of four hinge-supported, rectangular portal frames are reported. Two of the frames were subjected to a combined horizontal and vertical loading with a concentrated vertical load and a concentrated horizontal load applied at the midspan of the beam and at the top of one of the columns respectively. The loads were of equal magnitude in both tests. The remaining two frames were subjected to single concentrated loads; the first to a horizontal load acting at the top of one of the columns and the second to a vertical load acting at the midspan of the beam.

Three of the frames showed load carrying capacities in excess of those predicted by the simple plastic theory. The fourth frame, which was subjected to the combined vertical and horizontal loading, failed by lateral buckling of the beam section at a load slightly below the predicted ultimate load.

Details of a loading frame and a roller mechanism designed for these tests are indicated in Appendix A and B respectively.

ACKNOWLEDGEMENTS

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INTRODUCTION

The 1961 edition of the Canadian Standards S16 "Specification for Steel Structures for Buildings" is the first Canadian specification to include provisions for the use of plastic design. This introduction reflects the development, during recent years, of the methods of plastic analysis and their experimental verification. Plastic design is based on the important property of ductility and the ultimate load carrying capacity of the structure. Attention is focussed on the magnitude of the load causing collapse of the structure rather than on working loads referenced to the load producing initial yield. By employing this approach the designer has a means of providing a consistent margin of safety, with respect to collapse, for indeterminate structures. Collapse of an indeterminate structure occurs when the imposed loading causes the formation of a sufficient number of plastic hinges to produce a collapse mechanism. The collapse mechanism may involve the whole structure or only a portion of it if partial collapse occurs. According to the simple plastic theory, the structure, or a portion thereof, will undergo large deformations and collapse under the ultimate load.

The application of plastic analysis in the design of indeterminate steel structures, and of rigid frames in particular, has been the topic of numerous theoretical and experimental studies in recent years. Extensive research work into plastic

theory has been done at the University of Cambridge in England. The most significant experimental studies on this continent have been carried out at Lehigh University in the United States. Professor J.F. Baker, presently at Cambridge University, has probably made the most significant contributions to the development of plastic analysis. Baker, however, did not initiate plastic analysis, as Dr. Gaber Kazinczy of Hungary published results of tests of clamped girders as early as 1914.(1) Kazinczy suggested analytical design procedures and used them, apparently successfully, in the design of apartment buildings.

Professor Baker apparently was the first man to realize that the simple plastic theory that had been developed might well be the key to a rational design method for complete frames. Therefore, from 1936 to 1939, he carried out a series of tests(2) in the Civil Engineering Department at the University of Bristol in order to gain some knowledge of the modes of collapse of redundant structures. This first test series was conducted on miniature rectangular portal frames. The frames, having a ten inch height and twenty inch span length, were fabricated from small rolled steel H sections of $1\frac{1}{4}$ inch width x $1\frac{1}{4}$ inch depth. The material in the H sections displayed the typical yield of mild steel. Vertical concentrated loads were applied to the frames using a lever system of loading,

(1) Numbers in parentheses refer to references listed in the Bibliography.

the details of which are given in the reference.

In the first tests it was found that the beam to column connections were not completely rigid and furthermore that there was a small amount of rotation as well as displacement at the column bases which were assumed as fixed. Improvements were therefore made in the connections as the tests progressed. Baker pointed out that although such imperfections as were encountered would have resulted in a large discrepancy in any elastic calculations when compared to observed results, it was possible to compute the collapse load quite accurately using simple plastic considerations. Actual collapse loads observed compared quite favorably with the calculated collapse loads in all cases except one.

World War II interrupted Baker's experimental work. However, the work he had done to this time proved useful in the design of the "Morrison" air raid shelter[2] which was used during the war to provide home protection for families. The structure naturally had to be small if it was to be placed in a house and this consideration quickly ruled out the use of an elastically designed structure. If stresses were allowed to go into the plastic range, however, a compact rigid framework could be provided that would absorb a considerable amount of energy while the structure underwent large deformations. With this in mind, a framework was designed that was capable of withstanding the energy of a floor of fourteen feet span,

weighing twenty pounds per square feet, dropping from a height of nine feet onto the structure. Under this loading the top member of the rigid frame was to deflect downward a total of twelve inches which would leave the occupants lying in the shelter untouched. This structure required approximately one-tenth of the steel weight that the elastically designed structure would have required and its record of service during the war showed it to be quite satisfactory. This probably was the most unique set of tests to be conducted in plastic analysis.

After the war Baker undertook further research into plastic design at Cambridge University. These studies[2,3] were conducted to provide experimental verification of the various possible failure mechanisms that might be expected under various combinations of lateral and vertical loads applied to the frames. The cost of full scale tests would have been prohibitive and even tests on frames fabricated from H sections similar to those used in the first series of tests were too costly when the number required was considered. As a consequence, smaller frame specimens were formed using rectangular members. These frames were two inches high with a four inch span length and the column sections were one-quarter by one-quarter inch. The beam sections were one-quarter inch wide and the depths of three-sixteenth inch, one-quarter inch, and five-sixteenth inch were used in order

to obtain the various possible failure mechanisms.

Fifteen tests of these small portal frames were carried out with the bases assumed fixed in all cases, although it was again established that in fact small rotations did occur at the supports. Beam tests were conducted to determine material properties and all specimens were heat treated before testing to reduce residual stresses. None of the frames tested actually collapsed under the imposed loading but it was observed that the deflections were increasing quite rapidly at the calculated collapse load. In a few of the frames for final load increments, the deflection rate decreased slightly as the load increased. This phenomenom was attributed to strain hardening in the material at sections of large curvature, an effect which is neglected in the simple plastic theory. Baker reported, "In spite of this effect of strain hardening the agreement between the load calculated to cause collapse in a given mode and the region at which large deflections developed was so close that there was no doubt of the existence of the modes."

Baker was now ready to compare the theory with results obtained from tests of full-scale rectangular portal frames. Tests on such frames were carried out between 1948 and 1950.[2,4] These frames had a span of sixteen feet with a height of eight feet and were formed from eight inch by four inch joist sections throughout. They were tested in pairs as a stability meas-

ure and were spaced twelve feet apart. Load was applied both vertically and horizontally by adding weight in the form of caterpillar track links and water in large steel tanks attached indirectly to the frames at the desired load points. The vertical load was applied at the centre of the beam span and the horizontal load acted at the top of one of the column sections.

The first pair of frames tested had hinge supports and the vertical load was equal in magnitude to the lateral load, thereby subjecting one-half of the beam span to the full plastic moment. At a load of 5.75 tons the frames collapsed giving a favourable comparison with the calculated collapse load of 5.63 tons. The remaining two pairs of frames were tested with rigid supports and with a lateral load equal to twice the vertical load, which in this case again subjected one-half of the beam span to the full plastic moment. The calculated collapse load in both of these cases was $H = 2V = 11.25$ tons. In the first test a horizontal load of 13.11 tons was applied to the frame without causing collapse although large deflections occurred. During the second test the weld at one of the column bases broke at a horizontal load of 12.64 tons, well above the theoretical collapse load, and the test was discontinued. The excess carrying capacity of the fixed-base frames beyond the theoretical capacity was attributed again to strain hardening effects.

A considerable amount of work in connection with plastic

analysis has been carried out at Lehigh University under the direction of Professor Lynn S. Beedle. The first tests at Lehigh[5] reported in 1952 were carried out on two full-scale rigid rectangular portal frames. The frames were both of uniform section throughout, the first fabricated from 8 WF 40 and the second from 8 B 13 sections. The frames had a fourteen foot span with a seven foot column height, and were loaded with concentrated vertical loads at the three-eighth points of the beam span. The frames were provided with adequate support to prevent side-sway and lateral buckling. The frames had hinged support conditions and were loaded using hydraulic jacks, the load being measured using strain dynamometers in one case and with deflection dynamometers in the other. The paper describing these tests provides a detailed account of the testing techniques employed but only meagre test results. The results presented, however, are sufficient to show that one of the frames slightly exceeded its calculated collapse load while the second frame failed at a load slightly below the predicted value. Both frames exhibited a load capacity considerably in excess of that calculated to cause initial yielding of the members at the section of maximum moment.

These introductory tests at Lehigh were followed shortly by tests[6] on two more full-scale rigid portal frames, the results of which were reported in 1954. These frames were

fabricated from 12 WF 36 shapes with a column height of ten feet and a span of thirty feet. Horizontal loads, simulating the effect of wind, were applied simultaneously with vertical loads. The first frame tested was hinge supported and was subjected to vertical loads applied at the third points of the beam span together with horizontal loads equal to one-ninth of the magnitude of the vertical loads and applied at the third points of the windward column. All loads were applied by hydraulic jacks and strain dynamometers were again used to measure the applied loads. The beam portion was laterally supported using struts projecting from an adjacent wall and provisions were made to measure the loads induced in the struts by the lateral buckling tendency of the frame. The columns were laterally supported only at the top and bottom. The frame carried ninety-nine percent of its calculated ultimate load and finally failed by lateral buckling of the leeward column after considerable deflection had occurred.

The second frame of the series was tested with fixed supports and was also subjected to combined horizontal and vertical loading. This test differed from the first one in the application of the loads. The magnitude of the horizontal loads was maintained at one-ninth of the magnitude of the vertical loads until ninety-seven percent of the calculated ultimate load was reached after which the vertical load was held constant while the horizontal loads were increased until

collapse occurred. The horizontal loads were increased to ninety-five percent of their calculated ultimate value before collapse occurred. No lateral buckling was evident under the first loading increment but the beam finally buckled laterally during the second stage of loading. Large deflections again were observed before buckling occurred. The lateral support forces required to prevent lateral buckling were found to be relatively small in both tests.

The results of a series of tests conducted at the University of California were reported in 1960.[8] These tests are of particular interest in connection with the present studies at the University of Alberta, as a similar loading apparatus was developed for the tests conducted here. Three frames in all were tested in the California series. The first frame was subjected to a proportional loading with the applied loads increasing in their magnitude at the same rate, the second to a repeated lateral loading causing alternating plasticity in one of the members and the third to repeated lateral loading causing incremental collapse of the frame. Alternating plasticity and incremental collapse are beyond the scope of the introductory tests at Alberta and therefore a discussion of the results of those tests is omitted.

The frame subjected to the proportional loading had a six foot column height and a span length of six feet. The frame was of uniform section throughout, fabricated from 4 WF 13.

The ultimate load for the frame calculated on the basis of the conventional plastic analysis was found to be considerably lower than the observed ultimate load so a refined analysis assuming different plastic hinge locations was made. This still gave a conservative value for the ultimate capacity but was somewhat closer to the actual value observed in the test. The authors attributed the increased load carrying capacity to strain-hardening effects.

The results of the tests outlined in the preceeding paragraphs along with the results of tests investigating other aspects of plastic analysis have served to show that the plastic design theory is verified experimentally and can be used with confidence as a practical design method. European Building Codes were the first to take advantage of the new design concept. In 1948 a clause was added to British Standard No. 499, 'The Use of Structural Steel in Building ', allowing the use of plastic design methods. The American Institute of Steel Construction adopted its "Supplementary Rules for Plastic Design and Fabrication" in 1958. In accordance with these rules, the designer is allowed to employ plastic design methods in the design of continuous beams and one-and two-storey rigid frames and similar portions of structures rigidly constructed so as to be continuous over at least one interior support. A load factor of 1.85 is required for live load and dead load acting together and a load factor of 1.40 is required for the case

where wind loads or earthquake loads act in conjunction with the dead loads and live loads imposed upon the structure.

In Canada the 1961 edition of the Canadian Standards Association Specification S16 covering Steel Structures for Buildings contains a section on Plastic Design and Fabrication. This specification adheres quite closely to the A.I.S.C. "Supplementary Rules for Plastic Design and Fabrication" with the exception of one significant point. The C.S.A. specification allows the use of the plastic theory for the design of continuous fixed-ended floor beams in structures more than two storeys in height provided that the columns below the second uppermost storey have calculated stresses in the elastic range when the structure is subjected to the loads causing collapse of the plastically designed beam sections.

The introduction of the section covering plastic design in the C.S.A. Specification S16 is a definite indication that the use of plastic analysis in design has come of age in Canada and steel designers can look forward to a trend away from elastic design procedures for statically indeterminate structures.

A considerable quantity of information concerning the plastic action of steel frames and their structural components has been gained in recent years but there still is much to be learned if the use of plastic analysis is to reach its full potential. To introduce studies in plastic analysis at

the University of Alberta a series of tests was conducted in 1961. The test objectives were fundamental in nature but will provide a background for further studies.

SCOPE

It is the objective of the present program to provide a basis for future studies in the field of plastic analysis at the University of Alberta. The basic objective of the tests reported herein was to obtain ultimate load values for frames tested under various loading conditions and provide experimental verification of plastic theory.

The program consisted of load tests on four hinge-supported frames. The various loading conditions used are indicated in Figure 1. Frames 1 and 4 were subjected to the same loading condition. The "proportional" loading consisted of a vertical load applied at the center of the beam span and a horizontal load applied at the top of one column. Both loads were of equal magnitude. Frame No. 2 was loaded with a single horizontal load applied at the top of one column, and Frame No. 3 with a single vertical load applied at the center of the beam span.

In the test program, attention was focussed on the following behavior characteristics:

1. Actual load-carrying capacity of the frames as compared to the calculated capacity.
2. Deflections of the frames under load as compared to computed deflections.
3. The formation of plastic hinges at the sections of maximum moment.

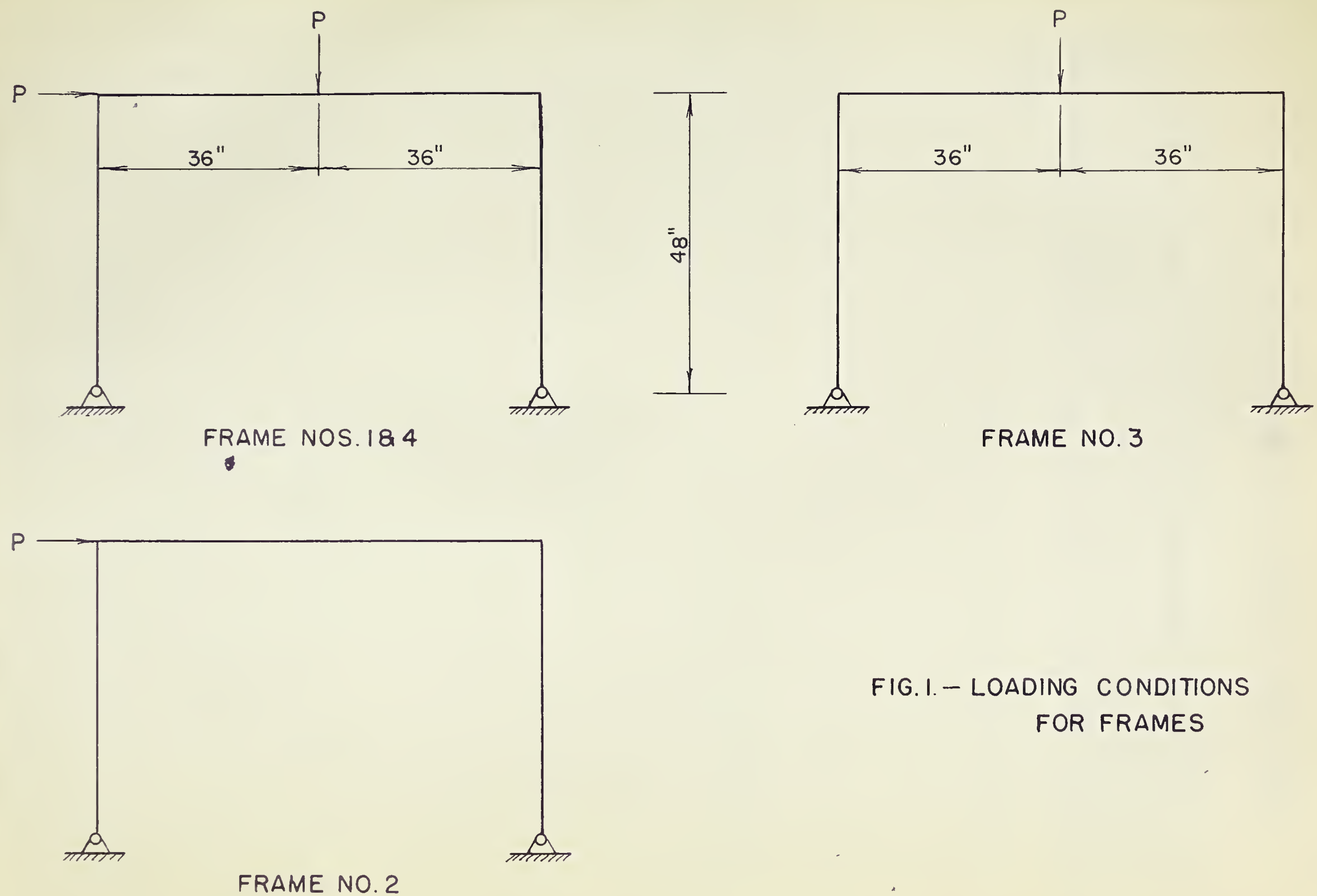


FIG. 1. — LOADING CONDITIONS FOR FRAMES

4. The failure mechanism formed in each frame at ultimate load.

The behavior of the loading apparatus during the tests was of particular interest since certain features departed from methods which had been utilized in previous investigations.

SPECIMENS

The four frame specimens were of uniform section throughout with column and beam sections cut from 4 I 9.5 material. They had a column height of four feet and a beam span of six feet as indicated in Figure 2. The holes at the column bases allowed the insertion of one and one-eighth inch diameter finished pins in order to mount the specimens in the loading frame. A hinged support condition was assumed to exist for this type of connection between the specimen and the loading frame.

The corner connections, shown in detail in Figure 3, were welded in order to obtain the greatest possible rigidity. The welds in the connections were proportioned such that the maximum weld stress at ultimate load did not exceed 1.65 times the allowable weld stresses given in the present elastic design codes. This is in accordance with the new C.S.A. S16 1961 Specification for Steel Structures for Buildings and with the A.I.S.C. Supplementary Rules for Plastic Design and Fabrication: Using these recommendations, the weld stress at the throat of the weld should not exceed 22,400 p.s.i. at ultimate load. The design stress on the leg of the weld then should not exceed 15,800 p.s.i.

Flange plates were welded to the beam at the connections so that the plastic hinges at the corners would form in the column section. The corner connections were well stiffened

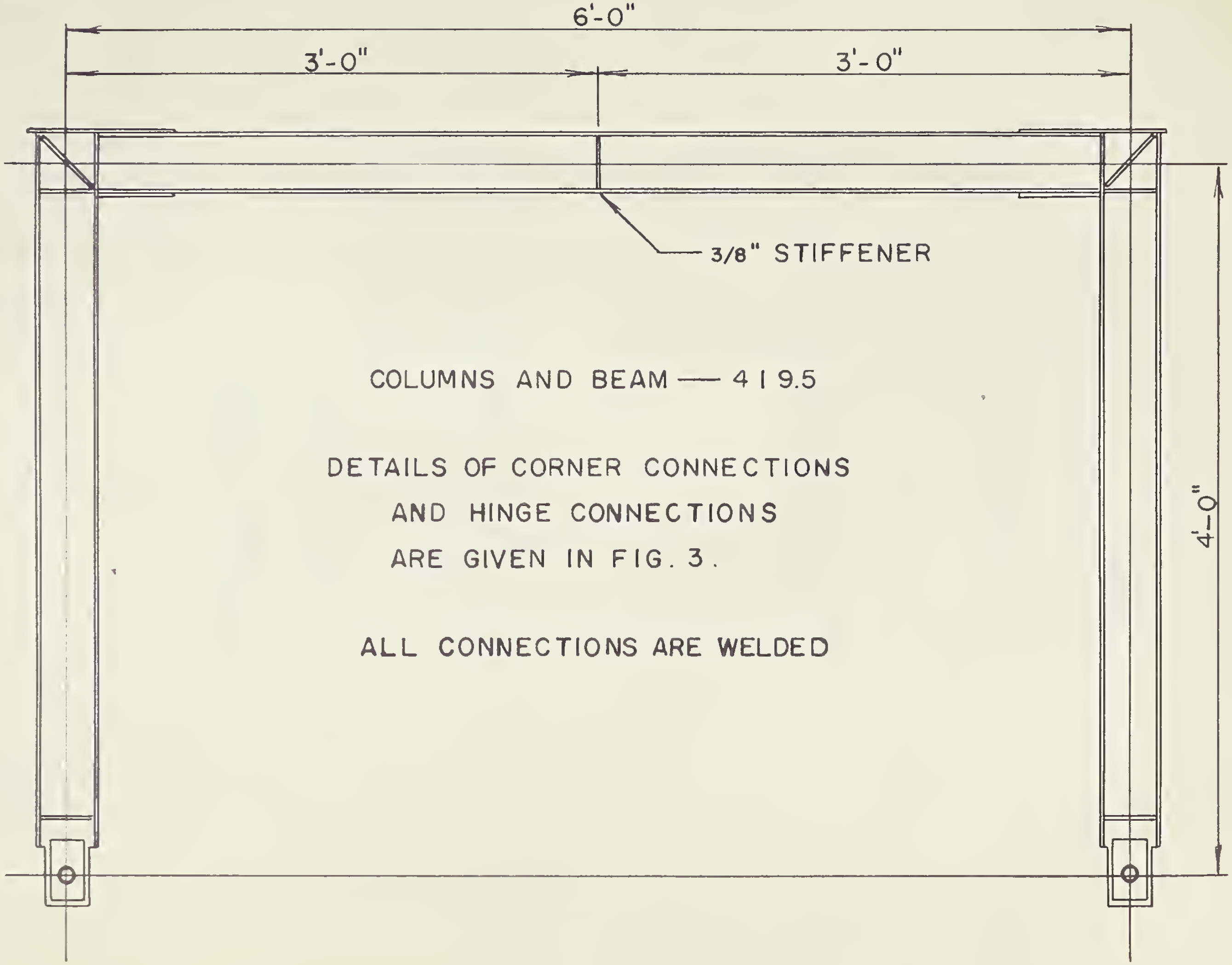
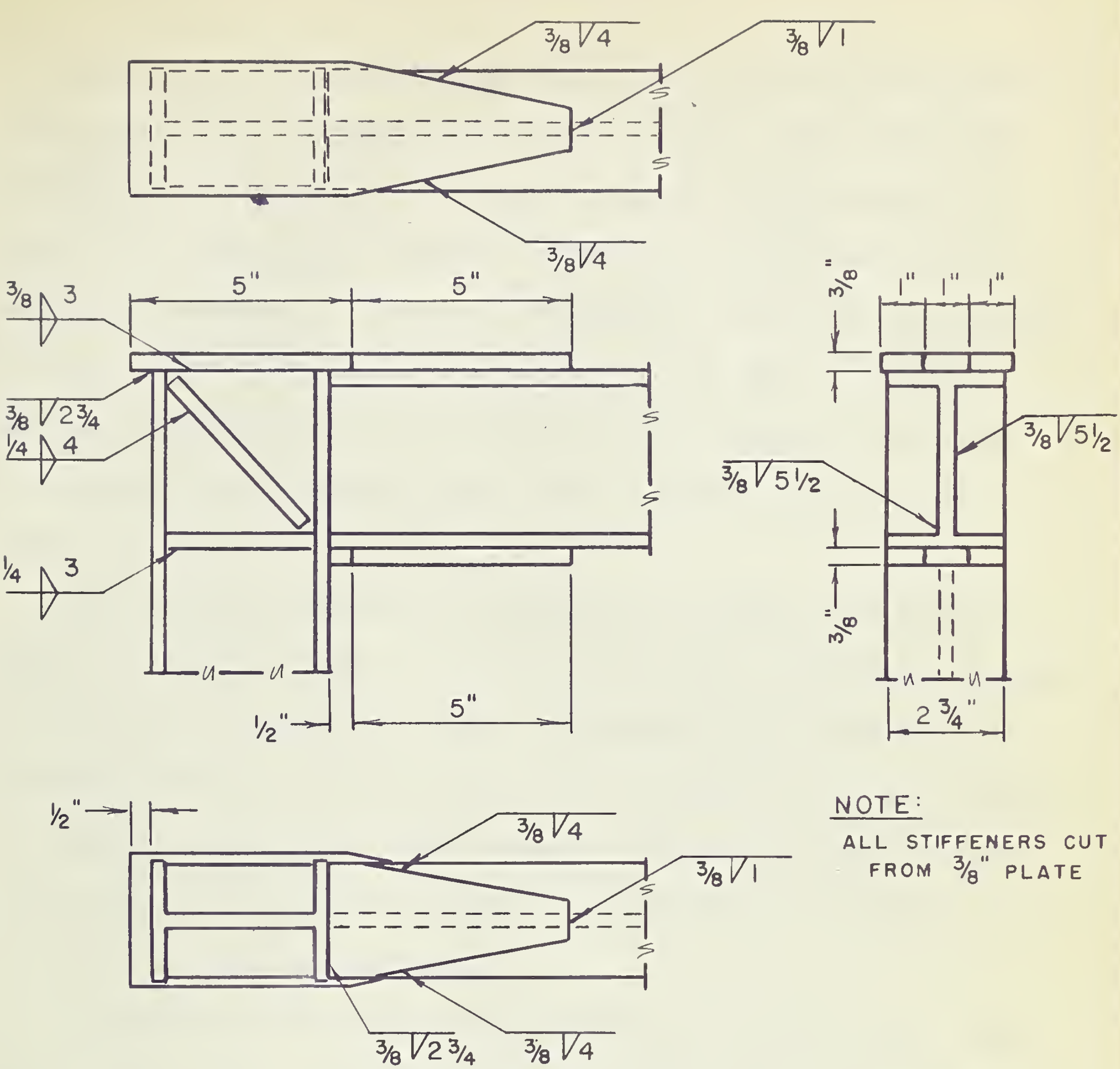


FIG. 2. — DETAILS OF RIGID FRAME

CORNER CONNECTION



HINGE CONNECTION

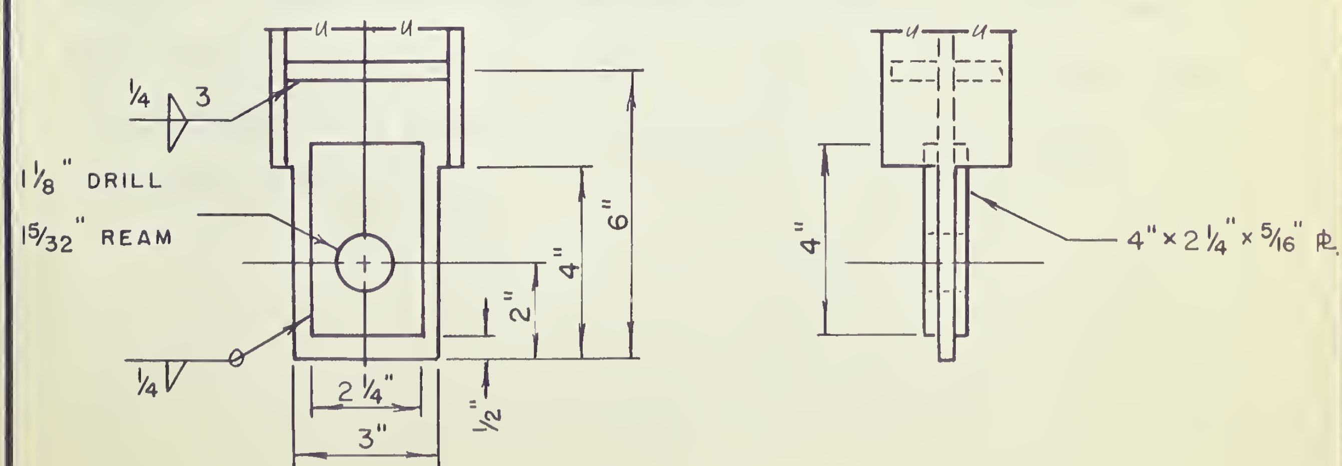


FIG. 3.—DETAILS OF RIGID FRAME

to assure that local buckling would not occur in the connections before the ultimate load was reached. The horizontal stiffener in the column web was designed to distribute the thrust from the lower flange of the beam and reduce the web crippling tendency. Diagonal stiffeners were used to resist the high shear stresses encountered in the web. Vertical bearing stiffeners were provided at the center of the beam to prevent web crippling under the vertical concentrated load.

The column flanges were coped at the base, as shown in Figure 3, so the frames could be fitted into the hinge support provided in the loading frame. Doubler plates were used to increase the bearing capacity of the column web at the hinge. The one and one-eighth inch diameter holes provided for the hinge pins were reamed to reduce the rotation resistance at the hinge as much as possible.

In addition to the frame specimens, the fabricator supplied three short sections of 4 I 9.5 material that were cut from the same stock used in the fabrication of the frames. Two coupons, cut from the webs of these sections, were used to determine the modulus of elasticity and yield point strength of the steel.

INSTRUMENTATION

A. Load Measurement

Loads were measured using a Baldwin pressure gauge designed for use with the hydraulic rams employed in the loading system. The gauge was calibrated in the University's 200,000 pound capacity Baldwin Testing Machine. Calibration figures are given in Appendix C.

B. Deflection Measurements

Two systems were employed in the measurement of deflections. "Federal" dial indicators, reading to 0.001 inch and having a one inch travel were used in the lower load ranges where deflections were small. For higher loads where the deflections exceeded the dial travel, a second system provided a means of measurement without resetting the indicators. In this system two surveyor's levels and two steel scales, graduated in 1/100 of an inch were employed. One of the scales was attached to a column, as shown in Figure 6, and one of the levels was focussed on it from a distance of approximately ten feet. Horizontal movement of the frame was observed by using the vertical cross-hair of the level to take readings on the scale at each load increment. The second scale was attached at the centre of the beam span as shown in Figure 7, and the horizontal cross-hair of the second level was used to take the vertical deflection readings at each load increment. Figure 4 gives an overall view of the test set-up show-

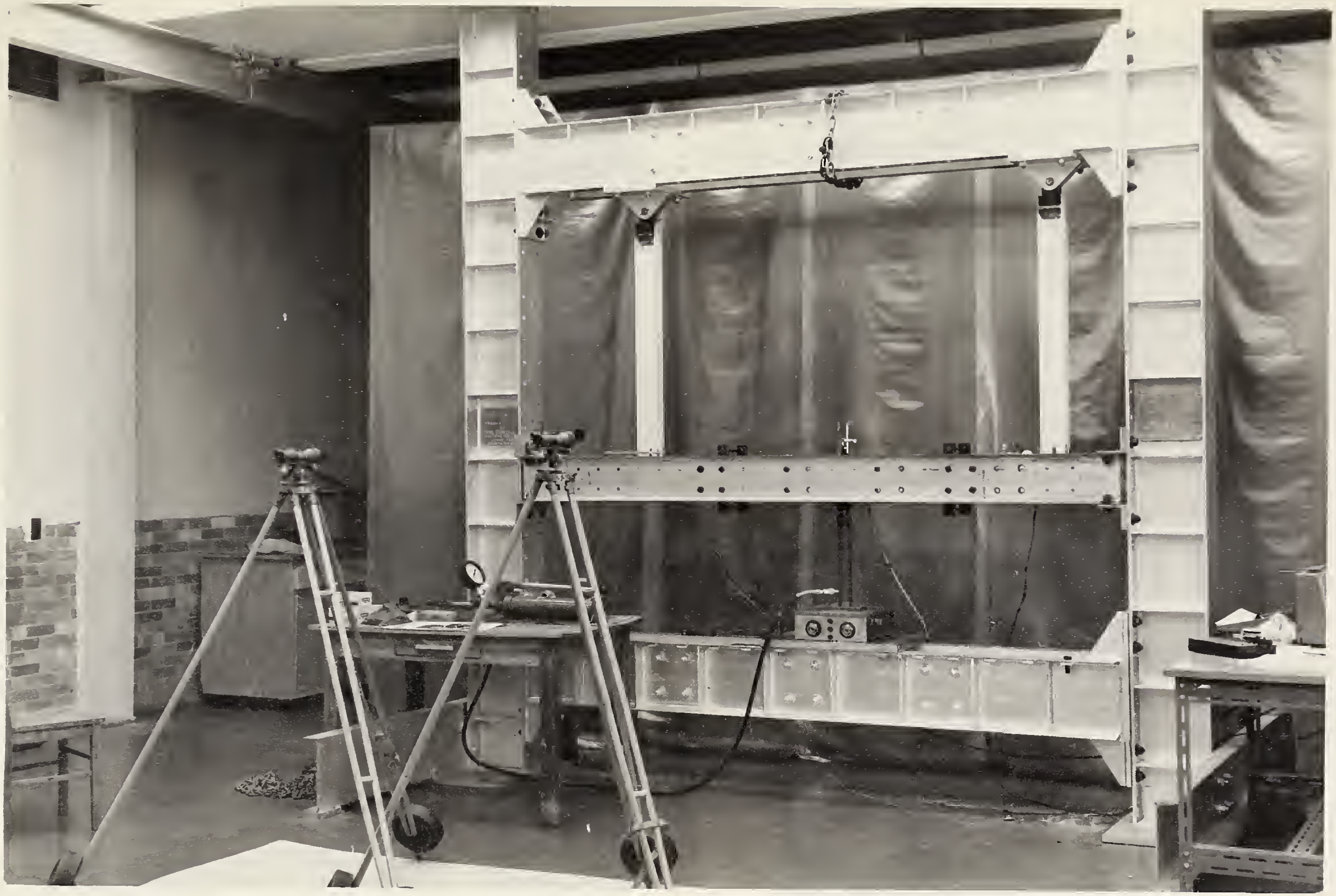


FIGURE 4 - GENERAL VIEW OF TEST APPARATUS

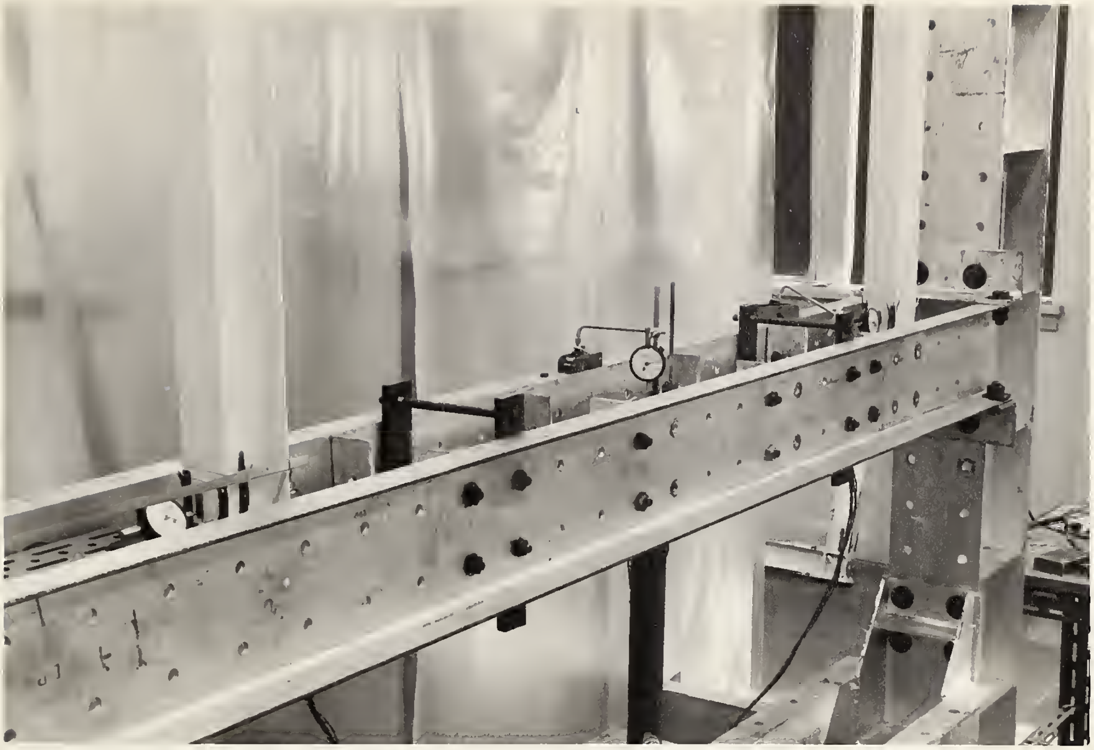


FIGURE 5 - GENERAL VIEW OF INSTRUMENTATION FOR DEFLECTION MEASUREMENTS

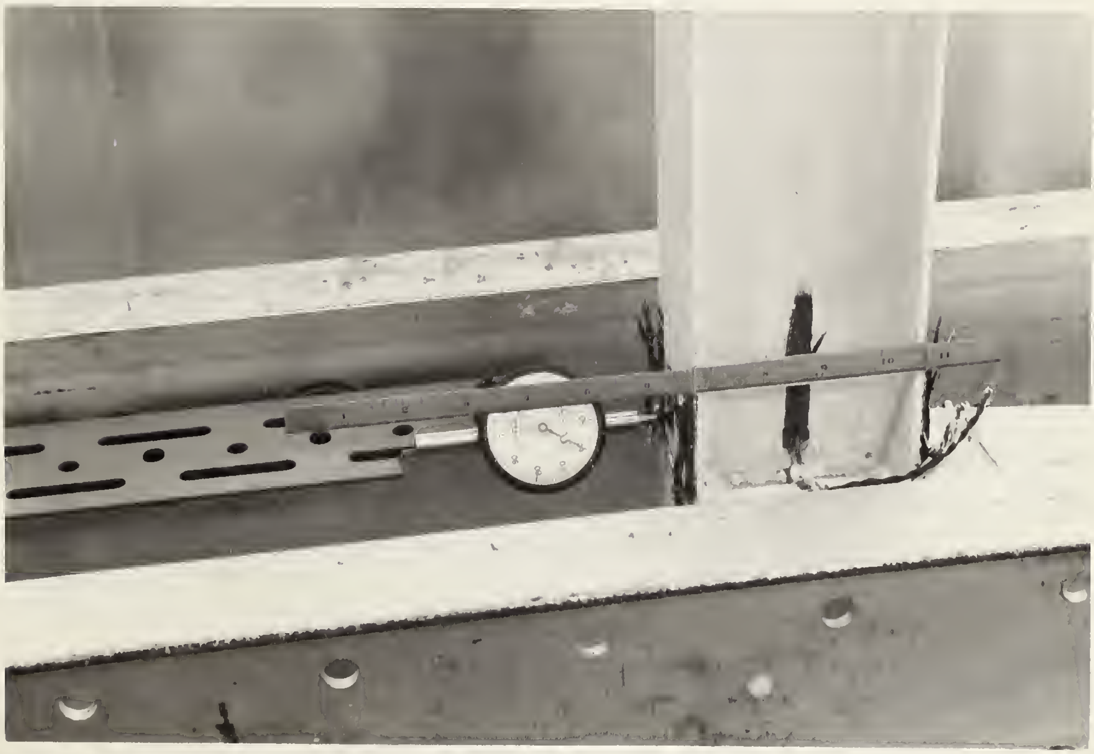


FIGURE 6 - DIAL AND SCALE INSTALLATION AT WINDWARD COLUMN

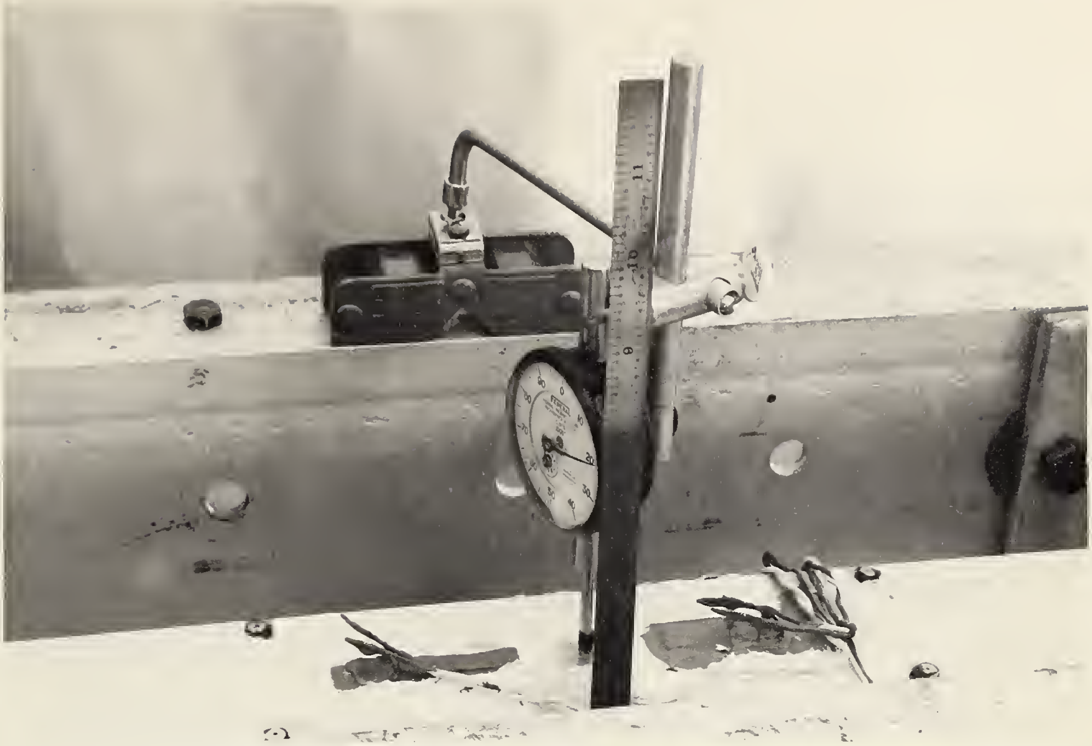


FIGURE 7 - DIAL AND SCALE INSTALLATION AT

MIDSPAN OF BEAM

FIGURE 8 - DIAL INSTALLATION AT

LEEWARD COLUMN

ing the levels in position.

In Figure 5 the dial indicators are shown in place for deflection measurements on Frame No. 3. A similar set-up was used for frames 1, 2 and 4 with the exception of the vertical deflection dial at the midspan of the beam. Horizontal movement of the beam under the action of the horizontal loading on these frames prevented effective use of the dial so vertical deflections were measured with the scale and level arrangement only. Figures 6, 7 and 8 show close-up views of the dial and scale installations at the windward column, midspan of the beam, and at the leeward column respectively. Horizontal movement of the roller mechanism was measured by means of a dial indicator in tests 1 and 4.

C. Strain Measurements

Electrical resistance strain gauges were used to measure strains at the locations where plastic hinges were expected to form. Sixteen Type A-3, SR-4 gauges were mounted on each frame, with six grouped near the top of each column and four grouped near the midspan of the beam as shown in Figure 9.

In preparing the metal surface for the gauges the mill-scale was removed and a smooth surface produced on the parent metal. This was a relatively simple procedure for the flange gauge locations where it was possible to use a heavy rotary-disc sander to do the job. The web gauge locations were somewhat more difficult to prepare because it was necessary to

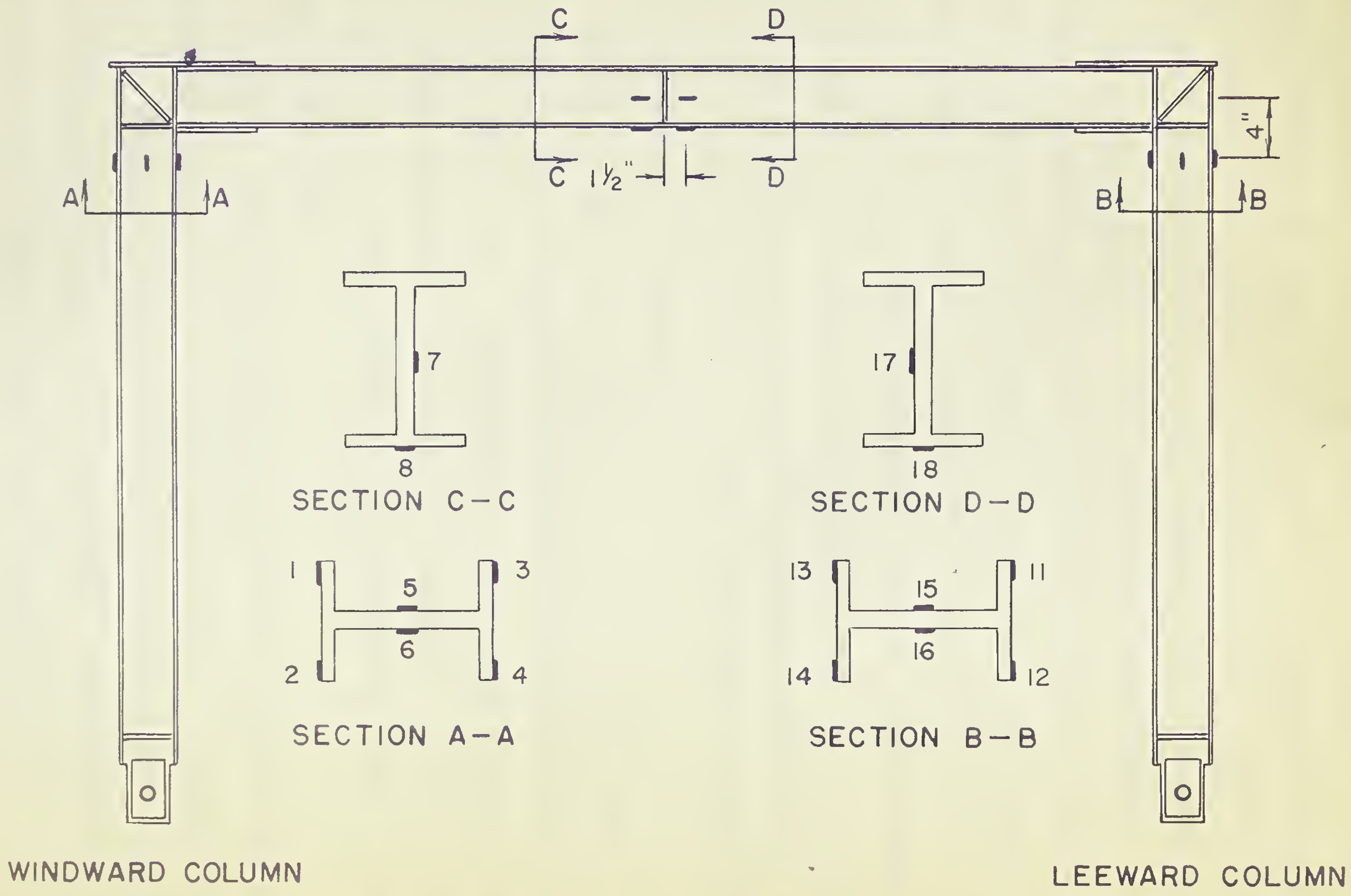


FIG. 9.— STRAIN GAUGE LOCATIONS

work in the restricted area between the flanges. A small rotary grinder was used which had to be handled very carefully in order to obtain the desired result. The surface was then cleaned thoroughly with acetone as recommended by the gauge manufacturer. The gauges were then mounted using a liberal quantity of C.I.L. Household Cement. Care was taken to squeeze out any air bubbles in the cement so that the gauges were in intimate contact with the parent metal of the frames. The cement was allowed to dry for approximately twelve hours. The gauges were then checked with an ohmeter. Defective gauges were removed and replaced immediately. When the gauges functioned properly they were waterproofed with two coats of neoprene.

After a frame had been set in place in the loading frame, the gauges were connected to a Baldwin-Lima Hamilton 20 Point Switching Unit. The connections at the gauges were soldered and waterproofed with two coats of neoprene. Strain readings were taken with a Baldwin-Lima Hamilton, Type 4, SR-4 Strain Indicator.

A Demec Gauge was employed to detect lateral buckling tendencies at midspan of frames 2, 3 and 4. The gauge points shown in Figure 7, were attached to the frames at their proper gauge distance by means of sealing wax. Readings were taken with the Demec Gauge at each load increment.

D. Stress Coating

After the frames had been set in place in the loading frame, they were given two coats of whitewash. The whitewash acted as a stresscoat so that the yielding could be observed as the plastic hinges formed in the frames.

LOADING SYSTEM

Loads were applied to the frame specimens by means of a self-contained system consisting of a "closed" loading frame and hydraulic rams. The loading frame was designed by the author for these tests and details of the design are included in Appendix A. "Blackhawk RC-161" hydraulic rams with a capacity of ten tons and a plunger travel of ten inches, were used to apply the loads.

The loading system used for tests 1 and 4 is shown in Figure 11. The horizontal load ram complete with the base-plate was bolted directly to the column of the loading frame as shown in the Figure. The vertical load ram was mounted on a roller mechanism designed to allow the necessary motion. Details of the roller mechanism, shown in Figure 10, are given in Appendix B. Friction between the rubber loading head of the ram and the frame provided the horizontal force to move the roller mechanism. The roller mechanism rolled on a roller plate attached to the lower beam of the loading frame. The test specimens were tested in what might be referred to as an upside down position with the hinged supports attached to the upper beam of the loading frame. Both rams were operated with a single "Blackhawk P-59" pump allowing equal loads to be maintained on the rams throughout the tests.

The loading system used for the second test is shown in Figure 12. The system was similar to that used for tests 1

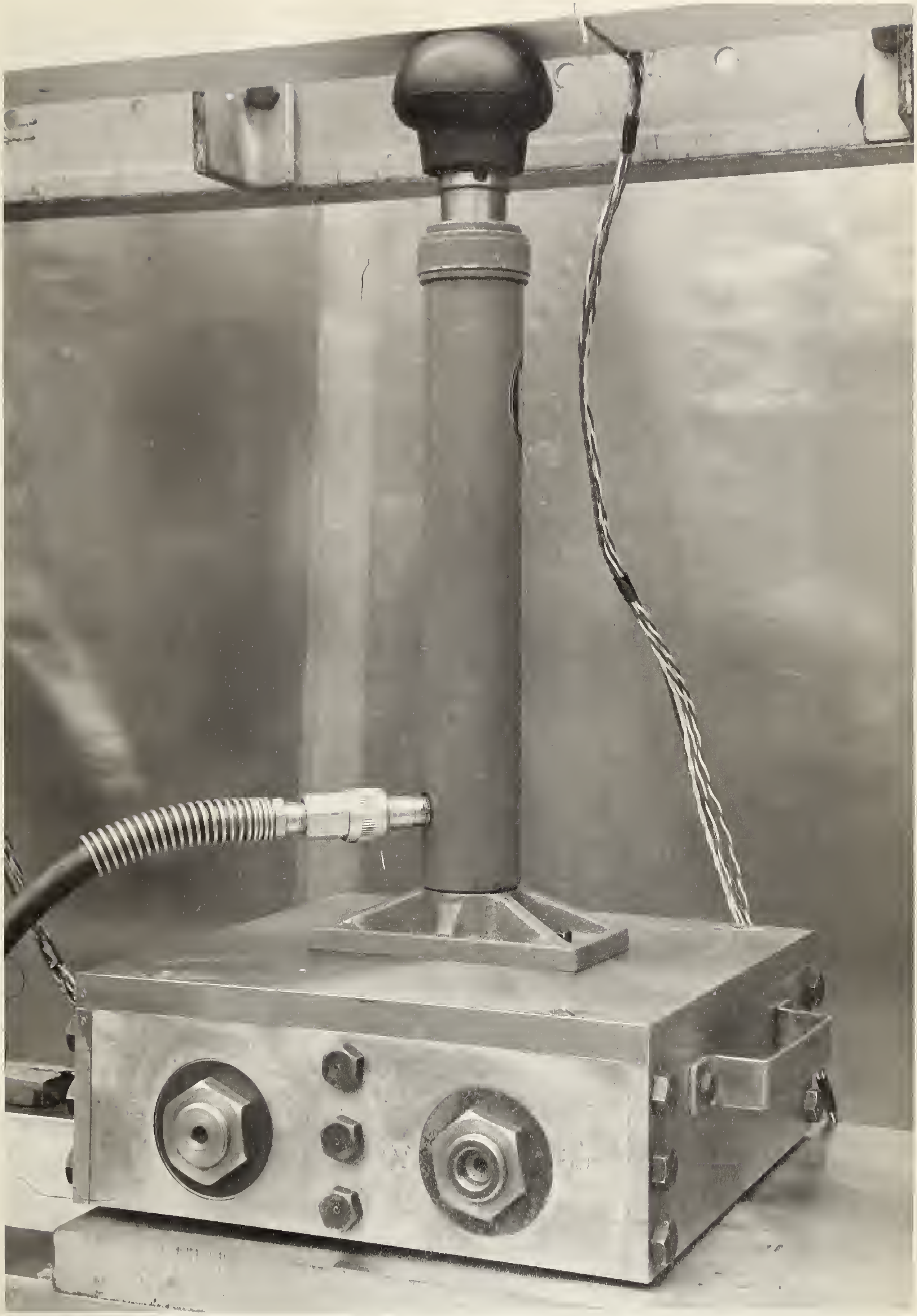


FIGURE 10 - ROLLER MECHANISM

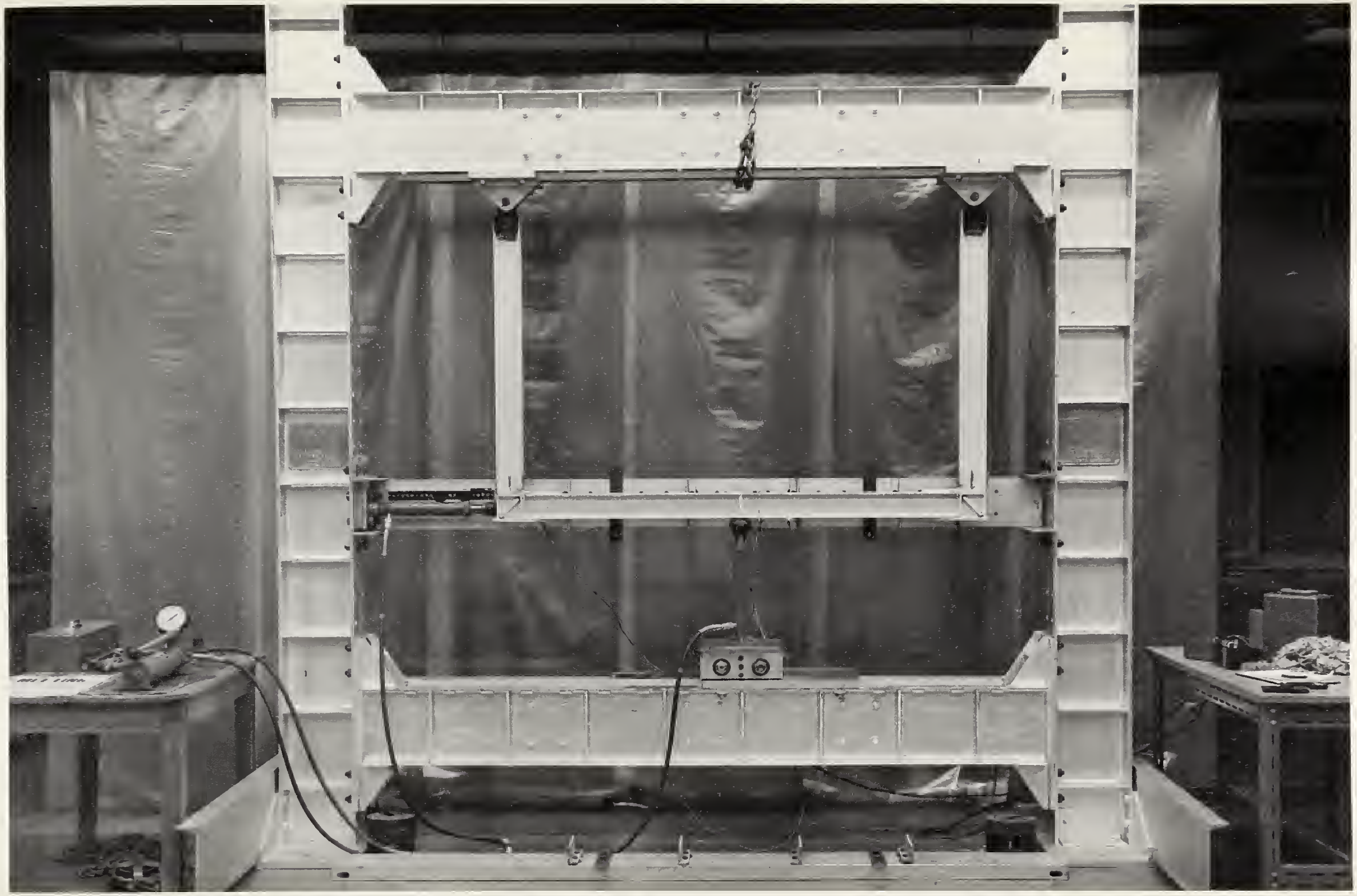


FIGURE 11 - LOADING SYSTEM FOR FRAME NOS. 1 AND 4

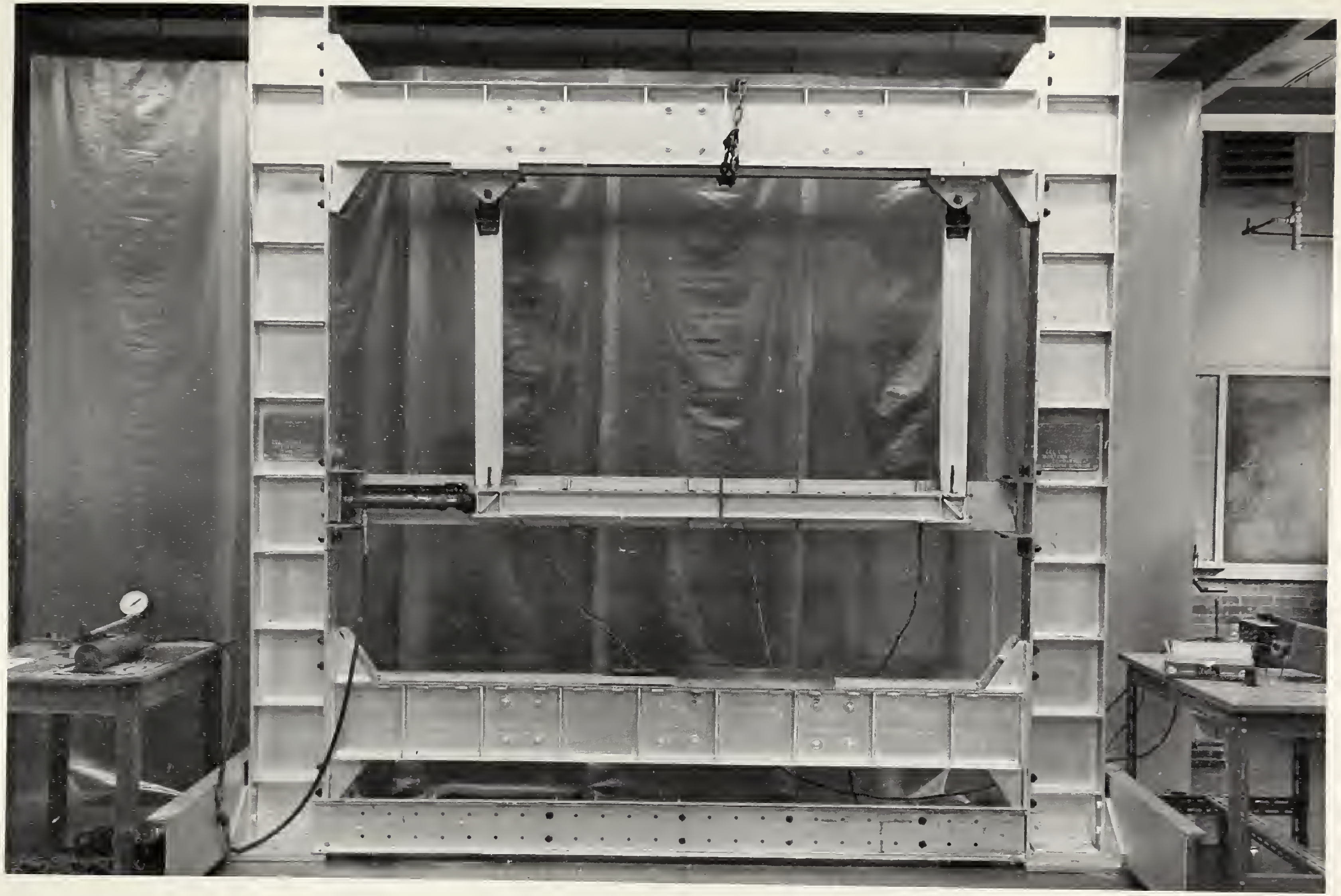


FIGURE 12 - LOADING SYSTEM FOR FRAME NO. 2

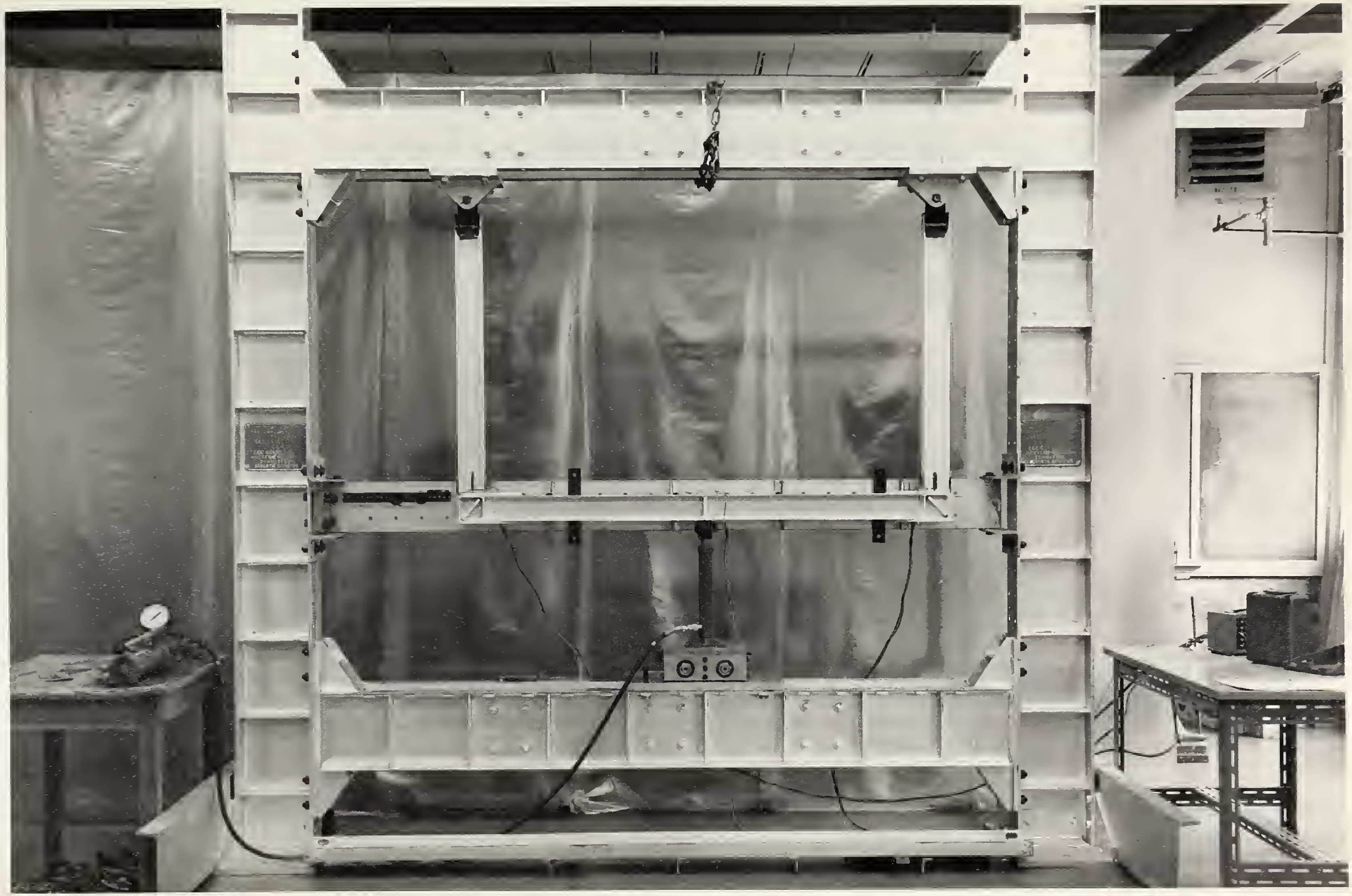


FIGURE 13 - LOADING SYSTEM FOR FRAME NO. 3

and 4 with the exception that no vertical load was applied. The horizontal load ram used was bolted directly to the column of the loading frame as in tests 1 and 4 and operated with the "P-59" pump.

Figure 13 shows the loading system used for the third test. No horizontal load was applied in this test so the vertical load ram could have been attached directly to the loading frame to prevent any horizontal deflection of the specimen frame under load. The ram, however, was mounted on the roller mechanism, as shown in the figure, so that there was very little resistance to horizontal motion offered by the loading system. The frame was then free to collapse by forming either a side-sway mechanism or a beam mechanism.

Lateral support was provided for the frames by channel sections shown in Figure 5. Structural angles projecting from the channels were used to produce contact with the specimens.

EXPERIMENTAL PROCEDURE

SR-4 strain gauges were mounted on each frame, checked for breakages, and given their initial coats of neoprene before the frame was positioned in the loading system. After each frame had been raised into position, the strain gauges were connected to the switch-box and the connections soldered before the final coats of neoprene were applied. After the neoprene had dried sufficiently, the whitewash stress coat was applied. The whitewash dried within three or four hours and the lateral support channels were then placed in position on both sides of the beam of the portal frame. Four $2\frac{1}{2}$" x $1\frac{1}{2}$" x 3/8" angle sections were connected to the back of each channel with their $2\frac{1}{2}$" legs projecting as can be seen in Figure 5. The short angle sections were "shimmed" to give one-sixteenth of an inch clearance between the angles and the edges of the beam flanges so that movement in the plane of the frame was not impeded by the lateral support system. Demec gauge points were then attached to the frame and the remaining instrumentation, consisting of the appropriate dials and scales, was properly positioned.

After the instrumentation had been completed, the hydraulic rams required for the particular test were placed in position. In tests 1, 3 and 4, where the roller mechanism was used, the roller was carefully aligned so that it would move parallel to the horizontal motion of the portal frame

without forcing the frame to drag heavily against the lateral support system. Surveyor's levels were placed in position shortly before the beginning of each test.

Three men were required to conduct each test. The first was in charge of the loading apparatus. His duties included applying the loads and maintaining the loads at the proper level while readings were taken. Leakage in the hydraulic system caused the loads to drop off if the system was left unattended. The second man took the demec gauge readings, read the deflection dials, and took the level readings at each load increment. He reduced the deflection dial readings immediately and plotted a load-deflection curve as the tests progressed. The third man took strain gauge readings at each load increment. The testing period for one test ranged from three to four hours.

Zero readings were taken in each test prior to the application of any load. The loads were applied using equal load increments on the pressure gauge. The gauge was calibrated to determine the actual load increments. Calibration figures are given in Appendix C. In the first test, loads were applied in pressure gauge increments of 400 lb. up to a gauge reading of 5600 lb. corresponding to an actual load of 5400 lb. Strain gauge readings and deflection readings were taken at each load increment. At this load, 5400 lbs., the load-deflection curve was beginning to bend away from the straight

line relationship so the gauge increments were reduced to 200 lbs. to give more points on the curve. Deflection readings were then taken with the surveyor's levels at each 200 lb. increment to the end of the test. Deflection readings with the Federal dial were discontinued when the load reached 6600 lbs. Strain gauge readings were continued at the 400 lb. gauge increments up to a load of 6200 lbs. before they were discontinued.

In the fourth test, loads were applied in pressure gauge increments of 400 lbs. up to a gauge reading of 7600 lbs. corresponding to an actual load of 7400 lbs. Strain gauge readings were taken at each increment up to this load. When the deflections began increasing rapidly, the Federal dial readings were discontinued because the deflection in a single load increment became greater than the dial travel. Deflection readings were taken with the surveyor's levels up until the end of the test. Demec gauge readings were taken at each load increment up to a load of 7000 lbs.

In the second test, the load was applied in gauge increments of 400 lbs. up to a gauge reading of 6000 lbs. corresponding to a load of 5750 lbs. Strain gauge readings, demec gauge readings and deflection readings were taken at each load increment. Beyond the 6000 lb. gauge reading, the gauge increments were reduced to 200 lbs. until the gauge reading reached 8200 lbs. corresponding to a load of 7900 lbs.

The gauge increments were then increased to 400 lbs. again until the end of the test. Strain gauge readings were taken at each 400 lb. gauge increment until the load reached 6500 lbs. when the readings were discontinued. Deflection readings were made with the Federal dials until the load reached 7900 lbs. and with the surveyor's levels until the end of the test. Demec gauge readings were taken until the end of the test.

The ultimate load on the third frame was expected to be somewhat greater than on frames 1, 2 and 4 so the magnitude of the load increments was increased. The loads were applied in 800 lb. gauge increments throughout the test with exception of the last increment which was only 200 lbs. The loading was discontinued at a gauge reading of 21000 lbs. which was 1000 lbs. greater than the rated capacity of the hydraulic ram. Strain gauge readings were discontinued when the load reached 17500 lbs. Deflection readings were made with the levels and with the Federal dials throughout the entire test with the exception of the dial at the midspan of the beam which was removed before the last load increment was applied. Demec readings were discontinued when the load reached 19950 lbs.

Two coupons cut from short pieces of stock supplied by the fabricator were used to determine the modulus of elasticity and the yield point strength of the material. The cou-

pons were tested in the Baldwin 200,000 lb. capacity testing machine with the automatic stress-strain recorder attached to draw the stress-strain curve. Two SR-4 strain gauges were attached to each coupon to provide precise strain measurements for the modulus of elasticity determinations. Load was applied to the coupons in 500 lb. increments until the yield point was reached. Strain gauge readings were taken after each load increment. The yield point load was read directly on the dial of the testing machine. After yielding occurred the load was applied continuously until the coupons failed. Two additional coupons were cut and tested at the A.S.T.M. specified maximum strain rate of 1/16 of an inch per minute per inch of gauge length in order to determine the effect of strain rate on the value of yield stress observed in a tension test. These coupons were tested in the Baldwin 200,000 lb. capacity testing machine and yield loads were read directly on the load dial of the machine.

MATERIAL PROPERTIES

Data obtained from tests on two tensile coupons taken from the web material are presented in Appendix E. Stress-strain curves were plotted from the SR-4 strain gauge data and were used to determine the modulus of elasticity of the frame material. These curves are shown in Figure 14. Both curves gave a modulus of elasticity value of 31.0×10^6 p.s.i. and this value was used in making theoretical deflection calculations for the frames. Values of the load at which lower yield occurred were read from the load dial on the testing machine. These values gave lower yield point stresses of 44.4 k.s.i. and 43.6 k.s.i. for coupons 1 and 2 respectively. An average value of 44.0 k.s.i. was used in computing theoretical load carrying capacities.

In conducting the above tests, it was necessary to apply the load in increments in the load range below the yield point so that strain gauge readings could be taken. Therefore the test was a slow test. A.S.T.M. Specification A 370-54T specifies that a uniform strain rate not exceeding 1/16 inch per minute per inch of gauge length should be used in a standard tension test after the load on the coupon reaches one-half of the yield point load. To check the effect of loading rate, two additional coupons were loaded at the specified maximum A.S.T.M. strain rate. Readings

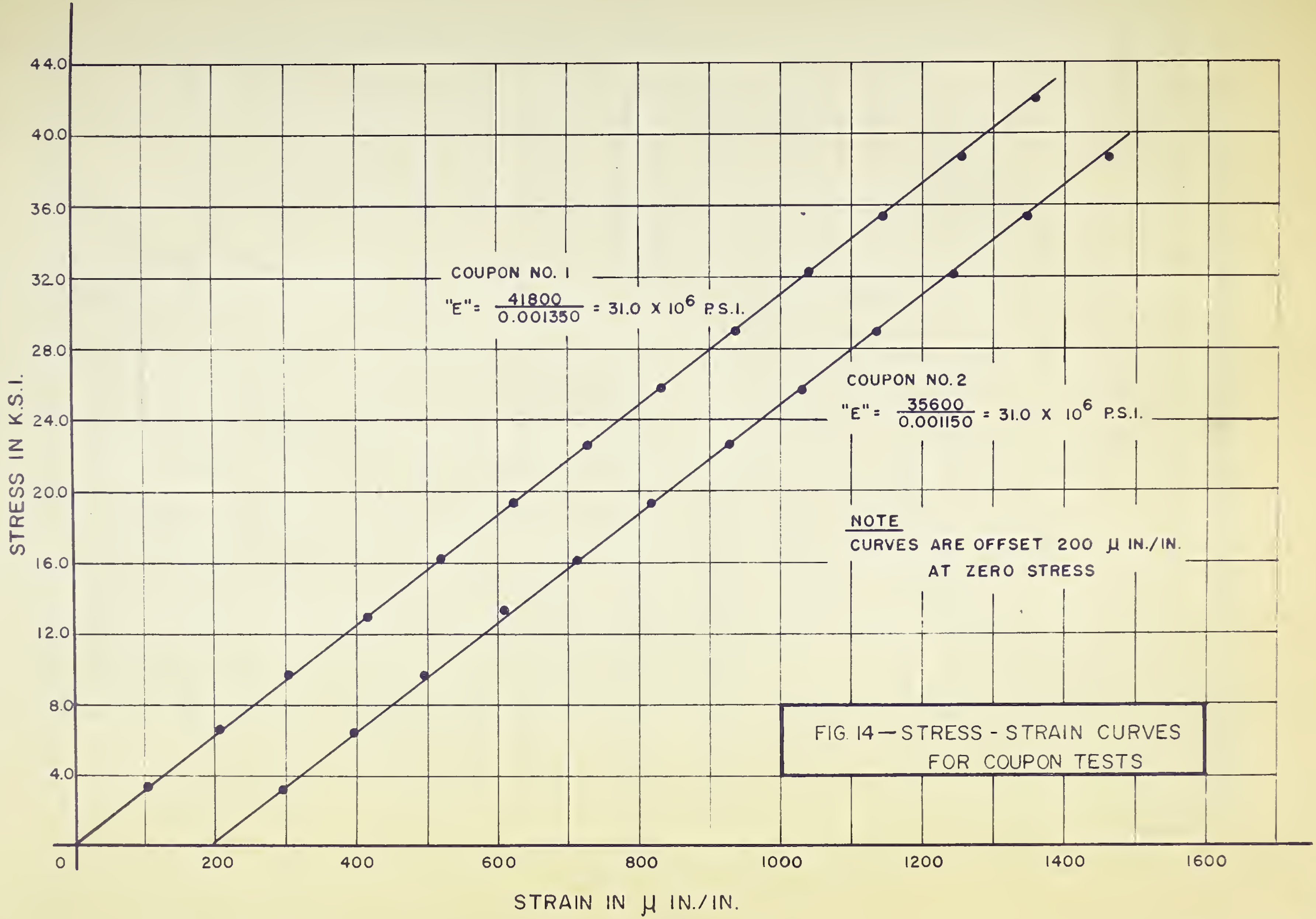


FIG. 14—STRESS - STRAIN CURVES FOR COUPON TESTS

of the lower yield load taken on the dial of the testing machine indicated lower yield stresses of 50.7 k.s.i. and 52.0 k.s.i. for these coupons.

TEST RESULTS

Test results are presented for each frame as follows:

1. Load-deflection curves for each load point.
2. Moment-curvature curves for the strain gauge locations at the top of each column.
3. Load-strain curves for the demec gauge locations at the midspan of the beam (frames 2, 3 and 4 only).
4. Photographs giving a general view of the frames after testing.
5. Closeup views of some of the plastic hinges formed.

The results for each frame are presented separately in the order in which they occur in the discussion.

The load-deflection curves were plotted using readings from the dial indicators whenever possible. Scale readings were used for some of the higher load ranges after the dial readings had been discontinued and were also used for entire load ranges in cases where it was not feasible to use dial indicators for any of the readings. Vertical deflections at midspan of the beam in Tests 1 and 4 were plotted using scale readings only. Horizontal deflections were measured at the top of the windward or loaded column. The data used in plotting the curves is presented in Appendix F. In addition to the observed deflections, a plot of theoretical deflections

has been made in each case to provide a means of comparing actual results with predicted results. In calculating theoretical deflections, plastic hinges forming at the corners of the frames were assumed to form at the corners of the line diagram representing the centrelines of the frame members. The theoretical deflections prior to the formation of the first plastic hinge were calculated using the Maxwell-Mohr equations, while deflections at ultimate load were calculated using the slope-deflection equations. Deflection calculations are included in Appendix D.

Plots of the moment-curvature relationship have been drawn for the strain gauge locations near the top of each column. These curves are based on assumed load-reaction relationships since no instrumentation was used to determine reaction components. Prior to the formation of the first plastic-hinge, the load-reaction relationship was assumed to be that determined by an elastic analysis of the frame. Upon the formation of the first plastic hinge, a new relationship was established on the basis that the plastic moment acted at the first hinge. This new relationship was then assumed to be true for the remaining load range up to the predicted ultimate load. Having thus established the load-reaction relationship for the entire loading range, it was possible to calculate the moments at the strain gauge locations for each load increment. Curvatures were calculated using the

SR-4 strain gauge data obtained from the four flange gauges near the top of each column. The average strain for the four flange gauges was found and divided by one-half of the member depth to obtain curvature values. Theoretical moment-curvature relationships for the 4 I 9.5 section have been drawn for comparison with the above curves. Calculations for the load-reaction relationships and for the theoretical moment-curvature relationships are included in Appendix D.

Strains measured with the demec gauge at midspan of the beam in Tests 2, 3 and 4 were plotted against load to show lateral buckling tendencies of the beam. The strains were measured at both edges of the lower flange of the beam. Differences in the measured strains at the same load increment presumably would mean that the beam was bending about its weak axis at midspan. Large differences in the strains would indicate lateral buckling of the beam. Demec No. 1 refers to the gauge points attached near the flange toe farthest from the reader, and Demec No. 2 to the gauge points attached near the flange toe nearest the reader when looking at Figure 4.

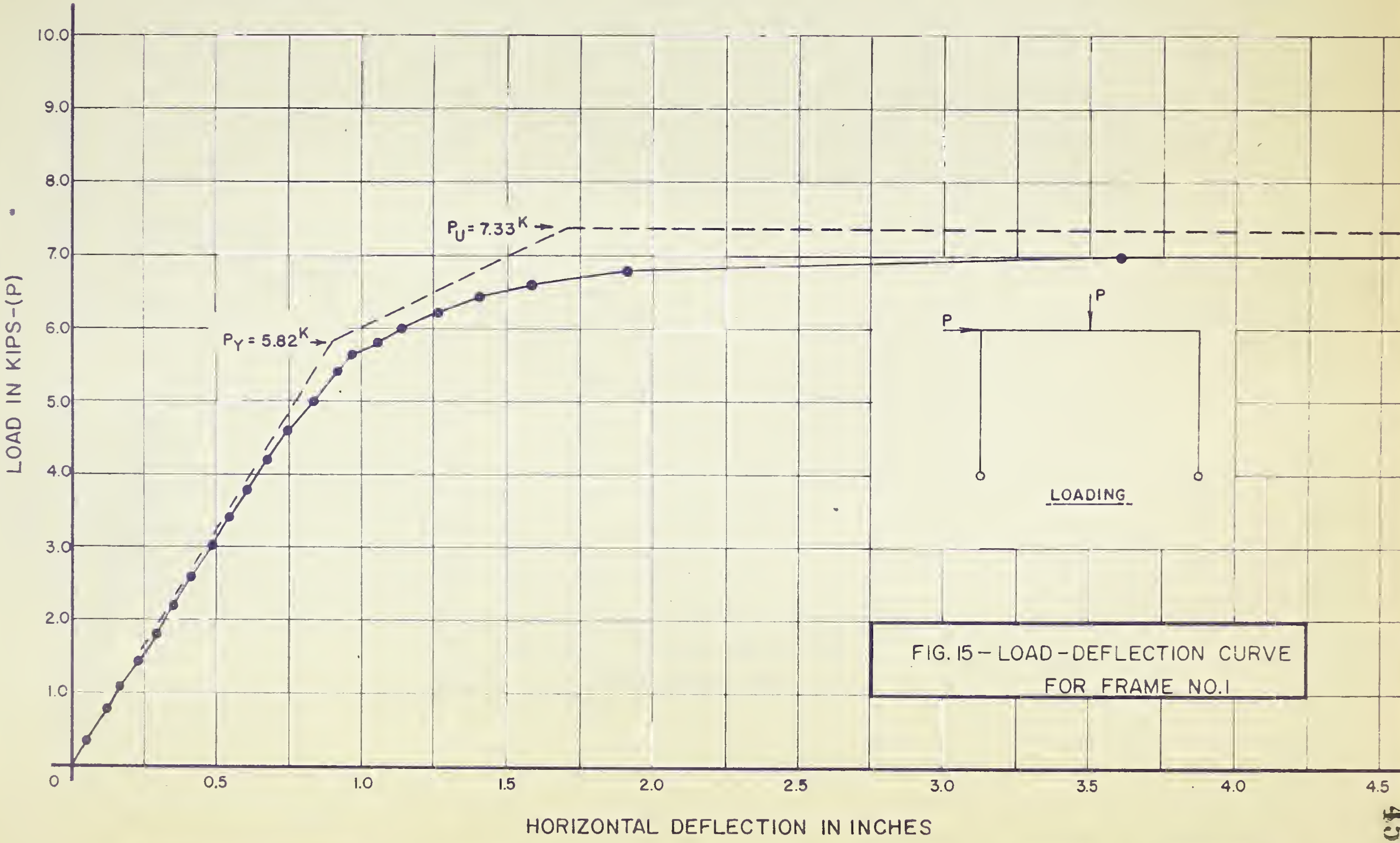


FIG. 15 – LOAD-DEFLECTION CURVE FOR FRAME NO. 1

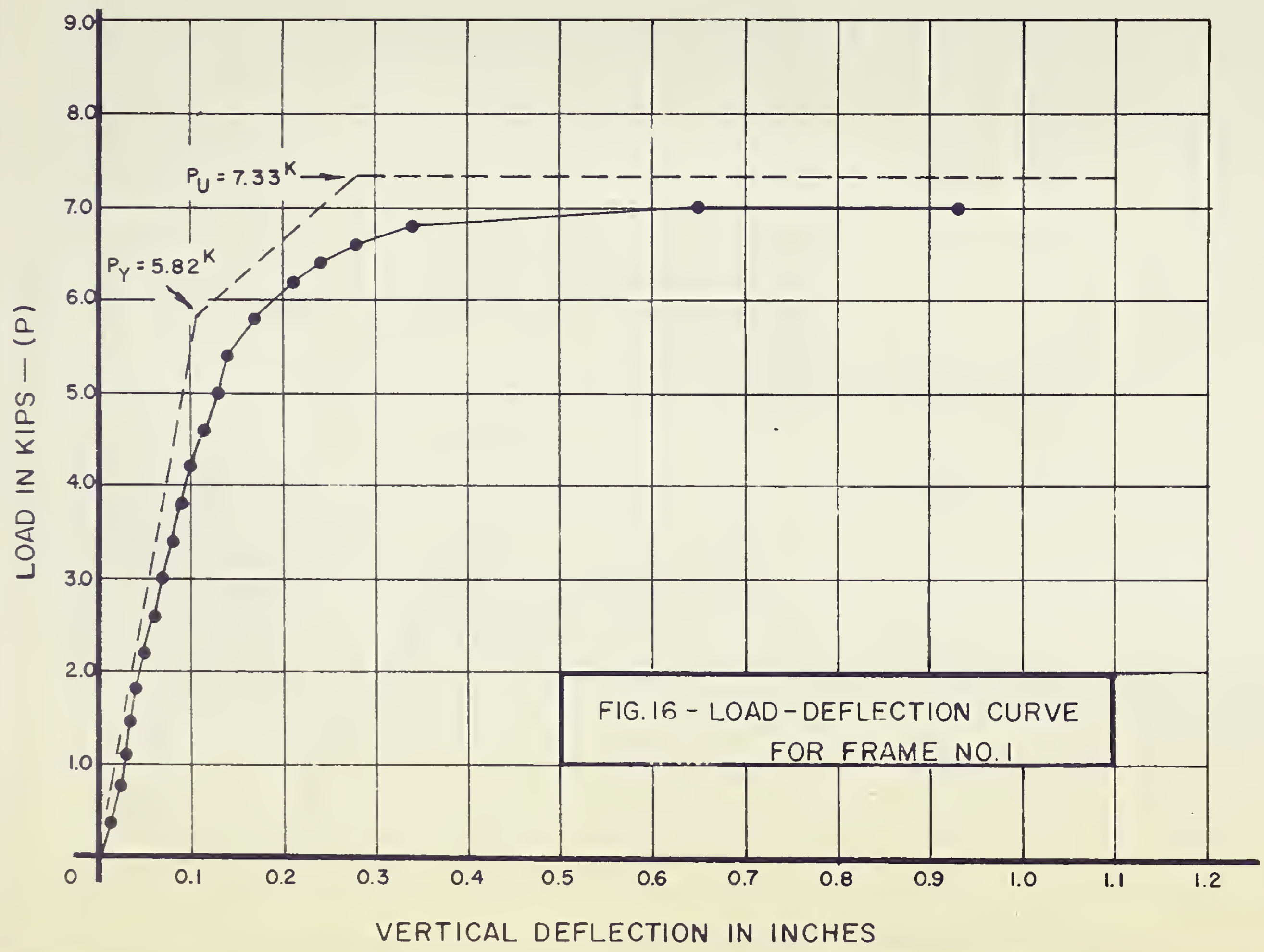
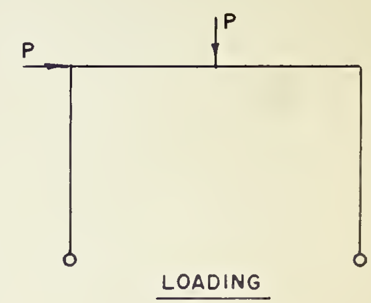


FIG. 16 - LOAD-DEFLECTION CURVE FOR FRAME NO. 1



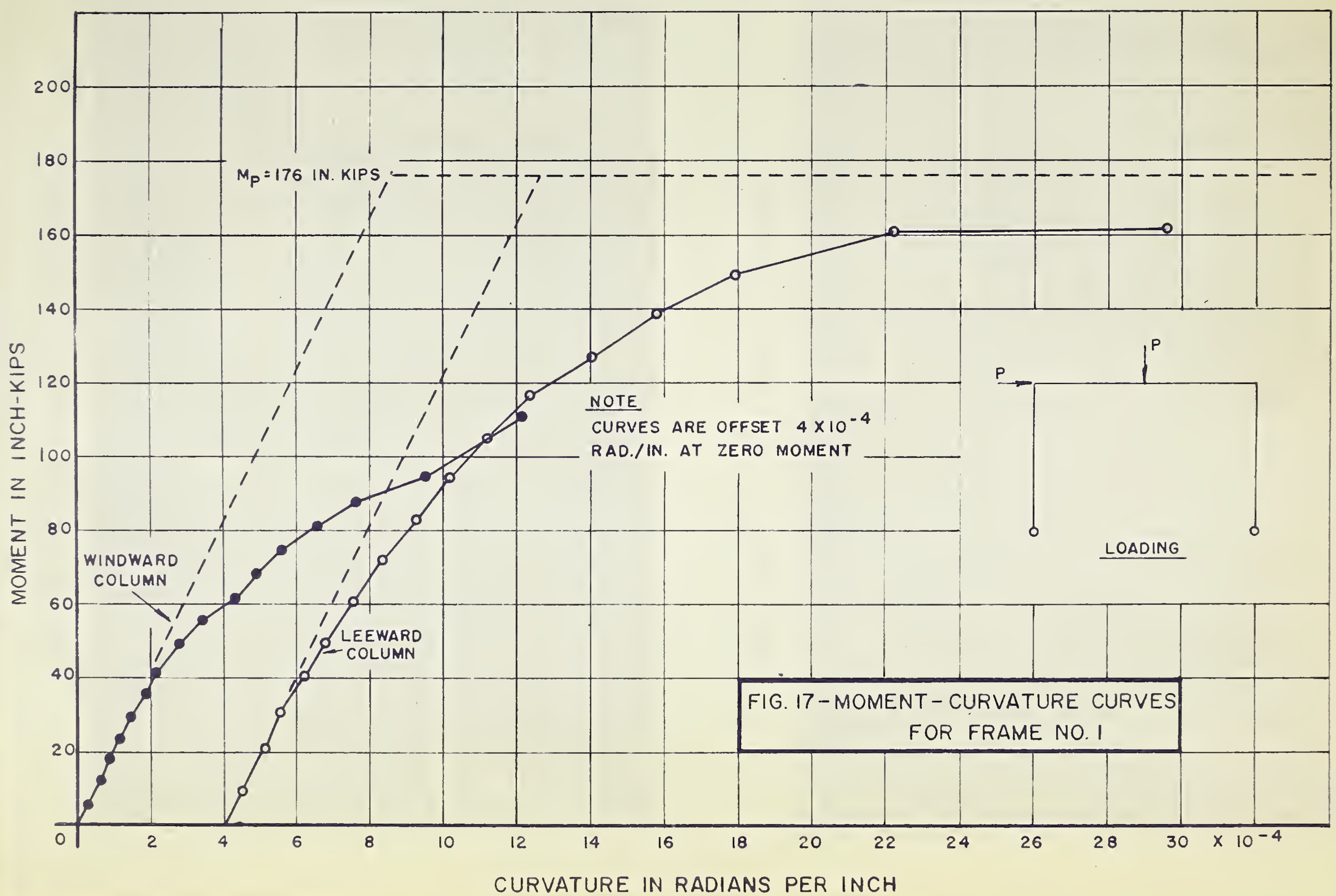


FIG. 17 - MOMENT - CURVATURE CURVES FOR FRAME NO. I

FIGURE 18 - FRAME NO. 1 AFTER TEST

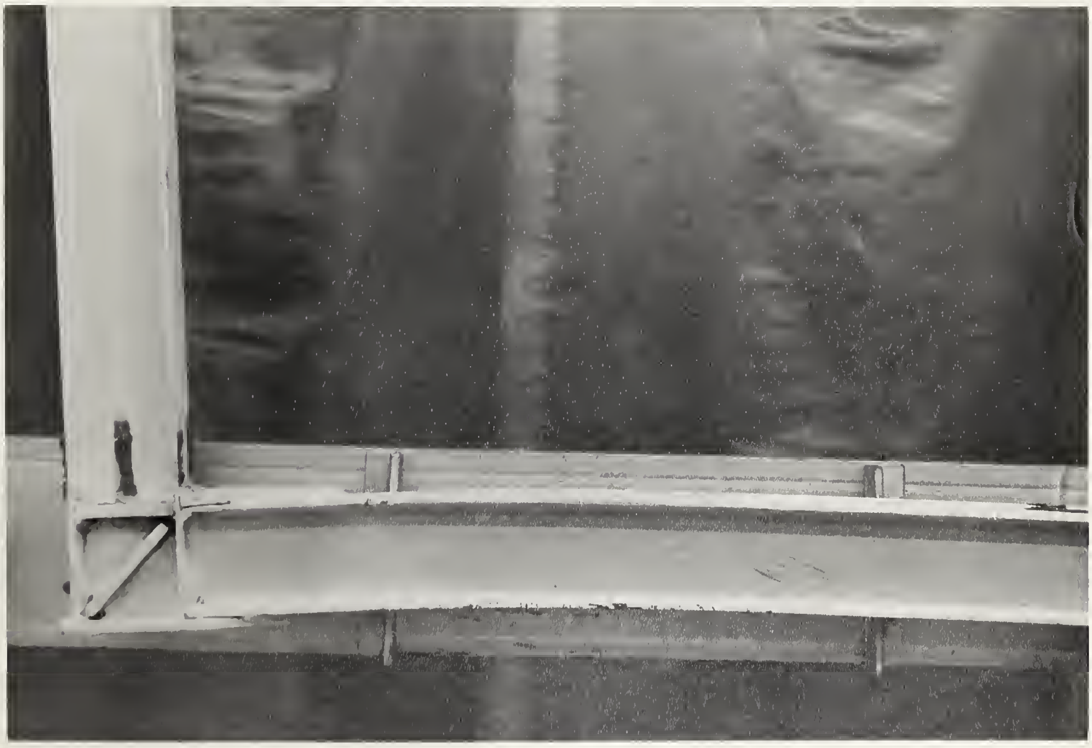


FIGURE 19 - WINDWARD PORTION OF BEAM

FRAME NO. 1

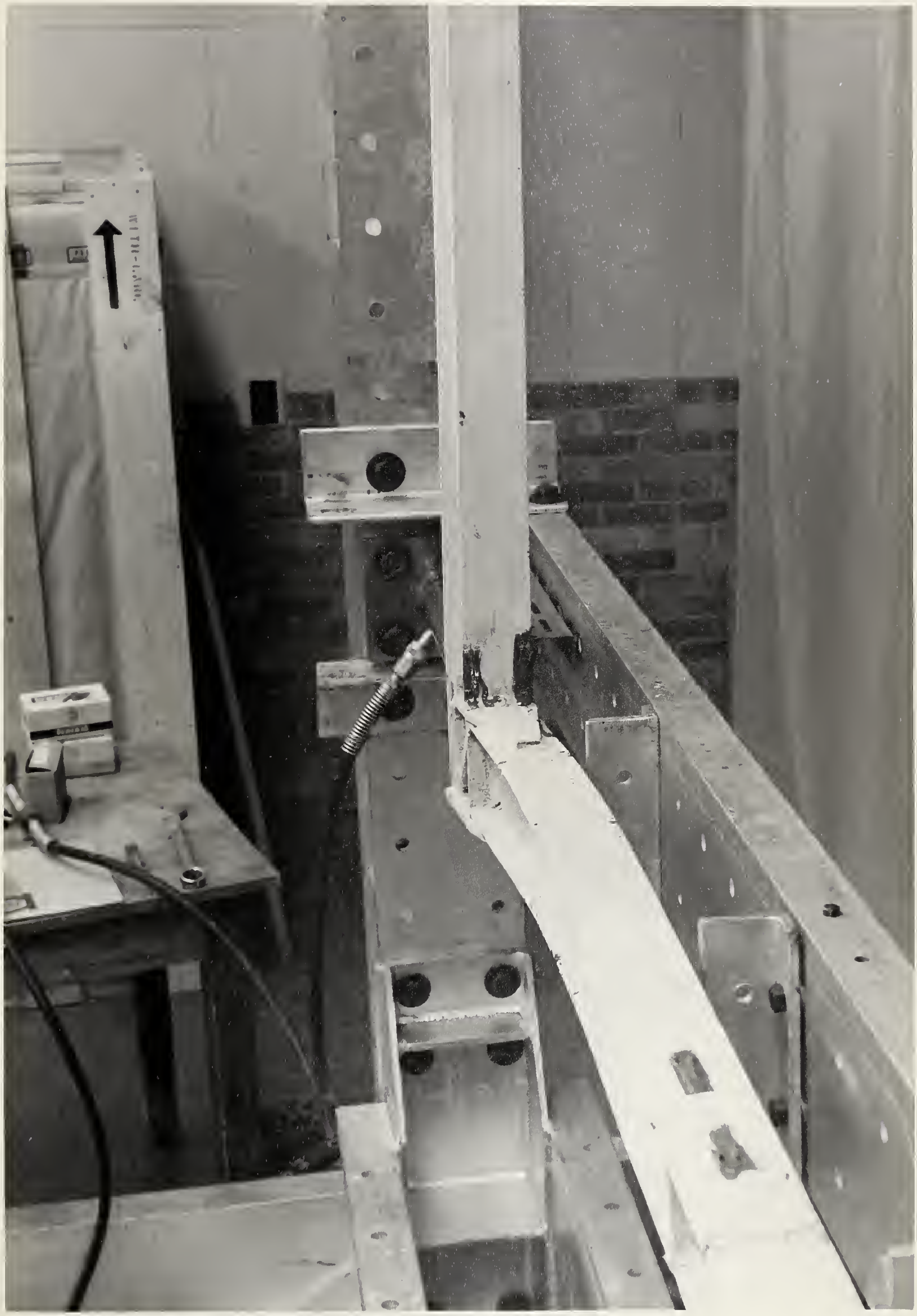


FIGURE 20 - BUCKLED PORTION OF BEAM

FRAME NO. 1

FIGURE 21 - PLASTIC HINGE FORMED IN
FRAME NO. 1

FIGURE 22 - LEEWARD COLUMN AFTER TEST
FRAME NO. 1

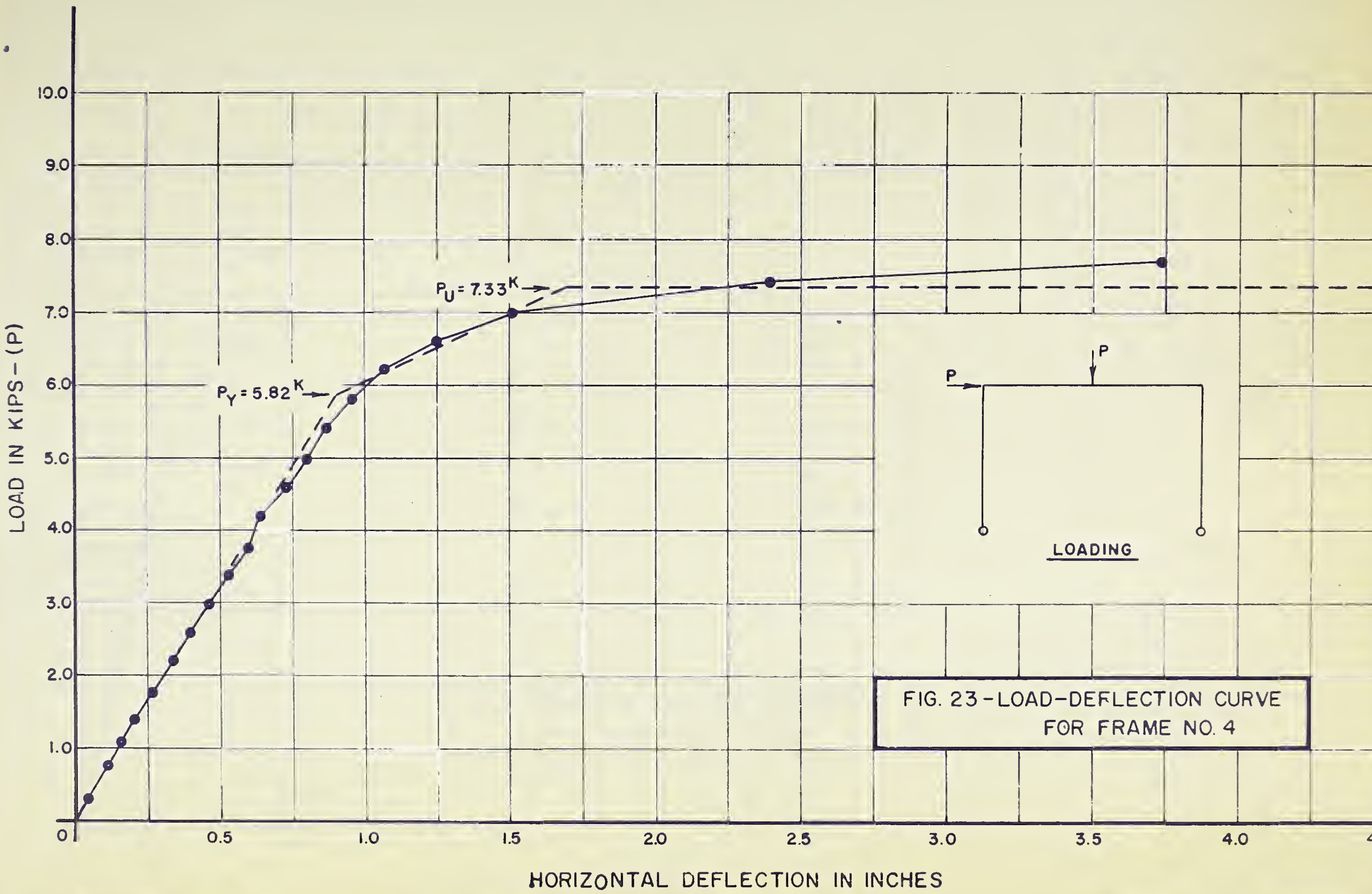
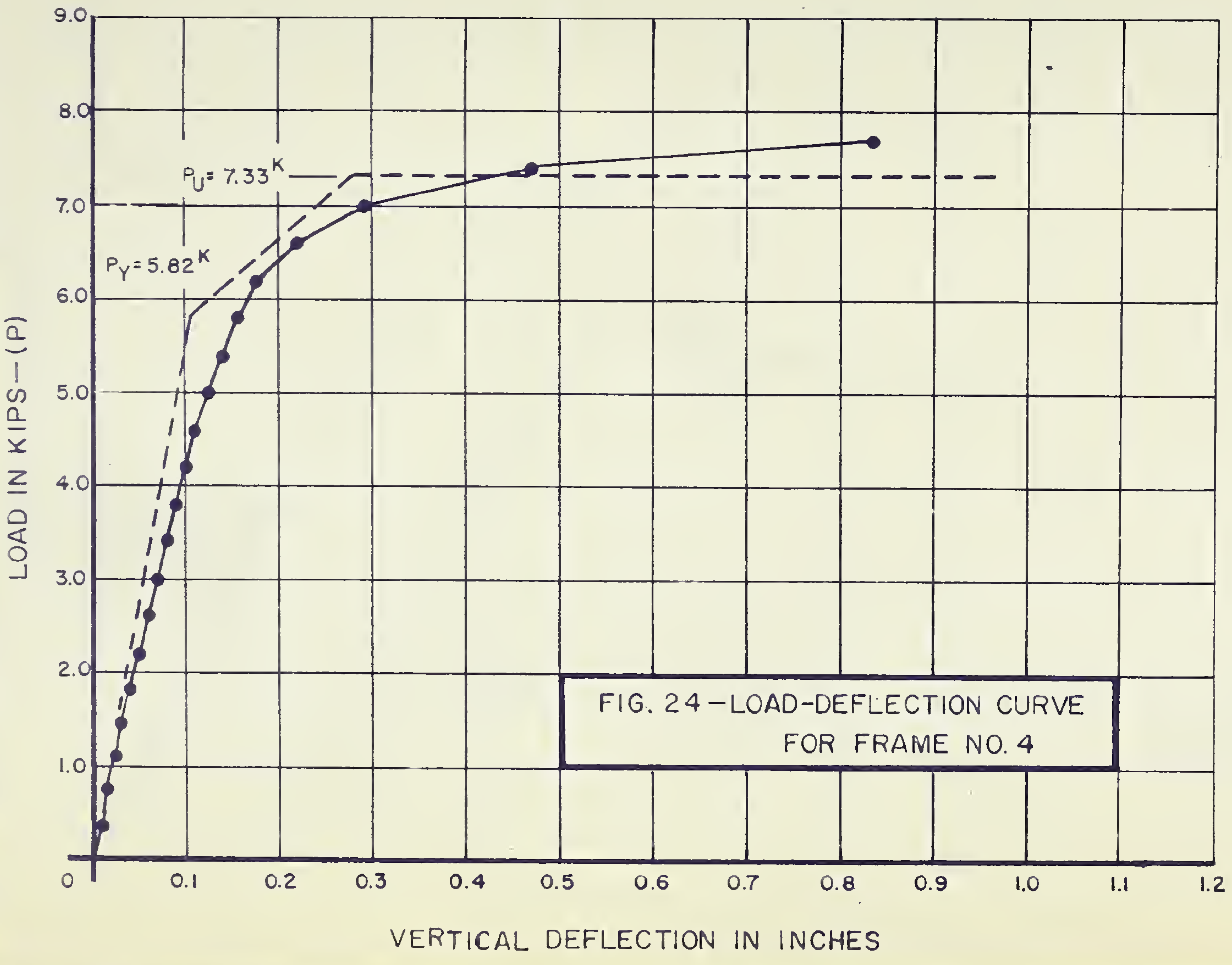


FIG. 23 - LOAD-DEFLECTION CURVE FOR FRAME NO. 4



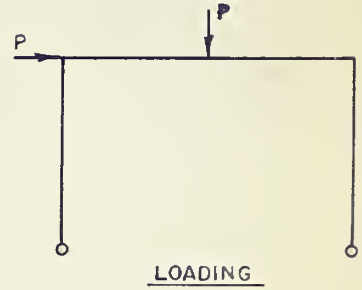


FIG. 24—LOAD-DEFLECTION CURVE FOR FRAME NO. 4

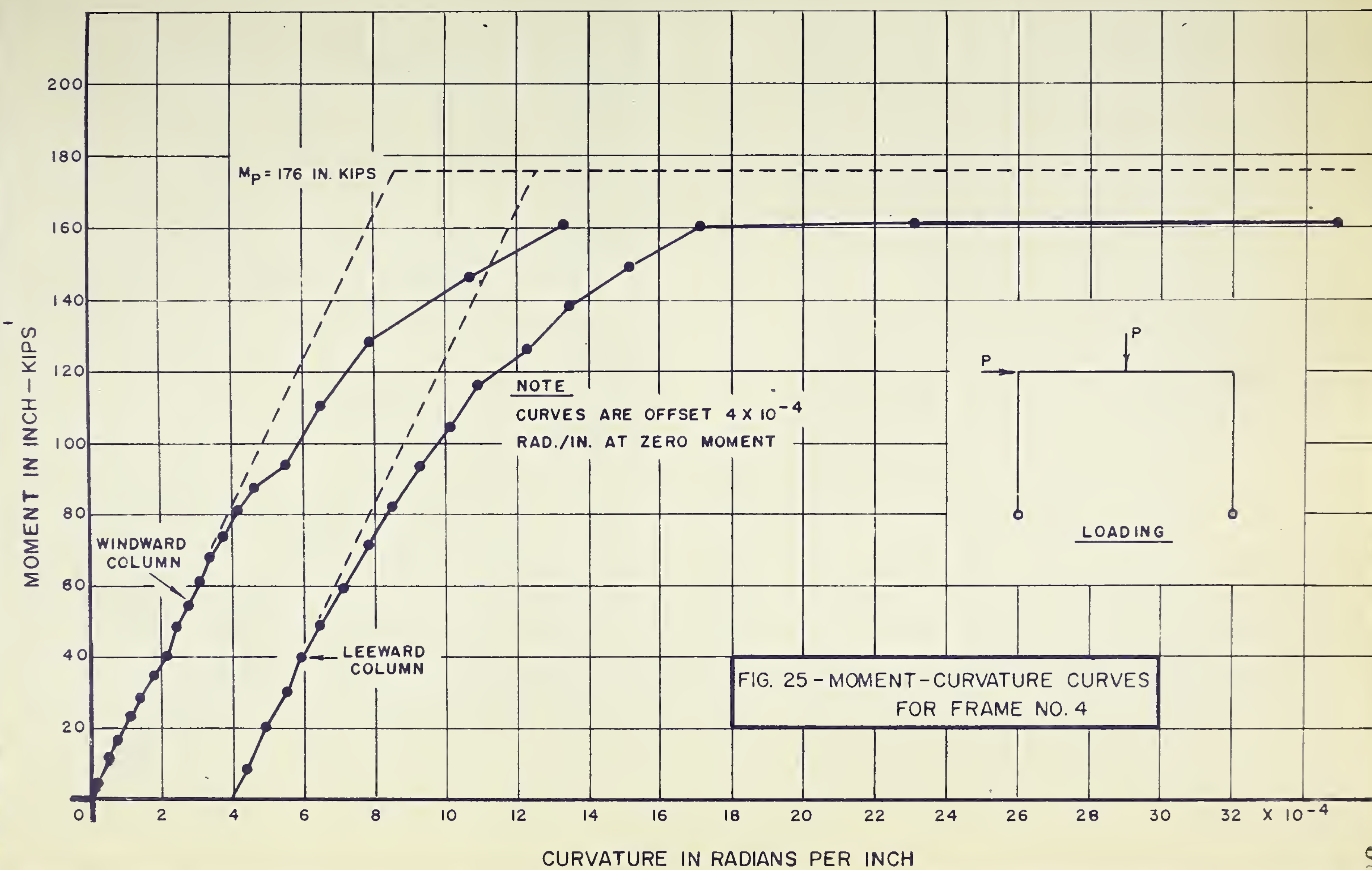


FIG. 25 - MOMENT-CURVATURE CURVES FOR FRAME NO. 4

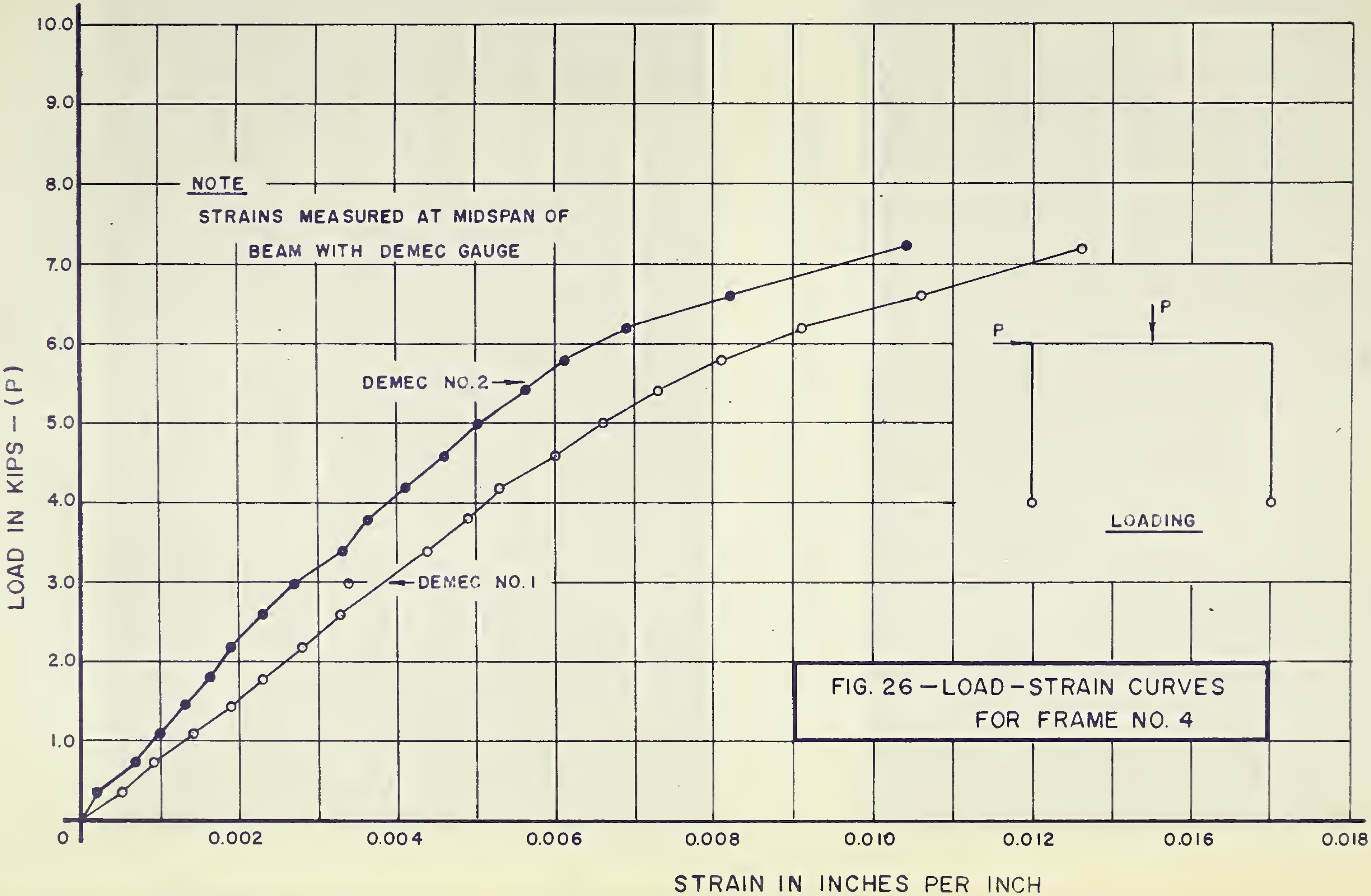


FIG. 26 — LOAD – STRAIN CURVES FOR FRAME NO. 4

FIGURE 27 - FRAME NO. 4 AFTER TEST

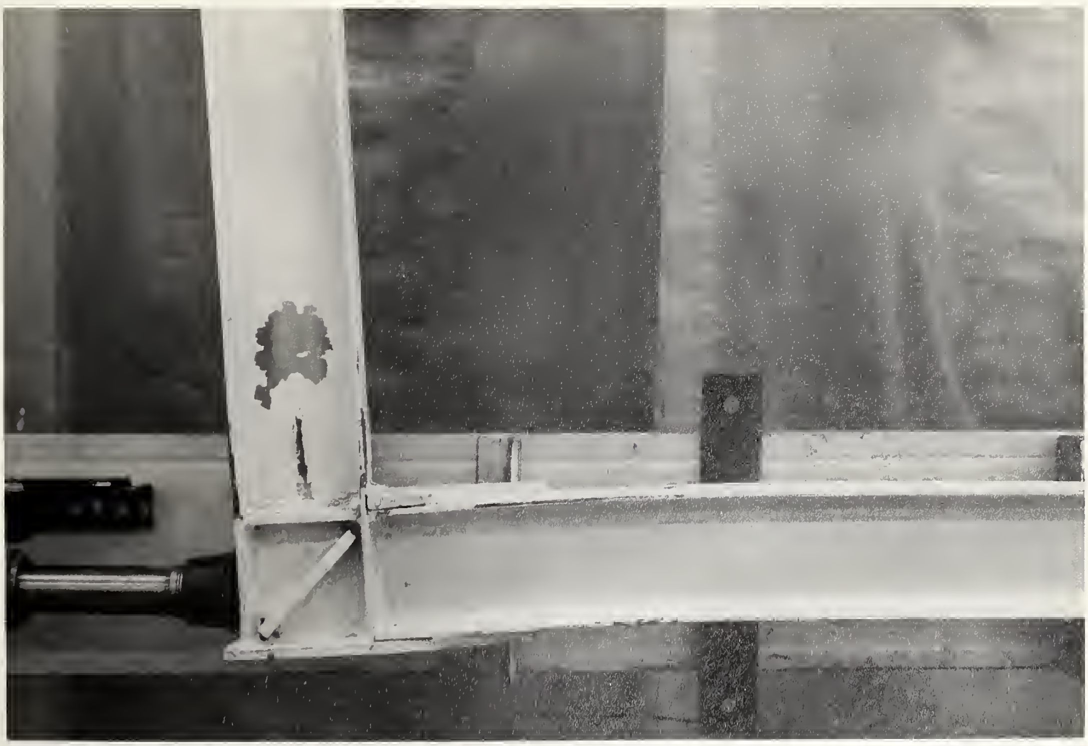


FIGURE 28 - WINDWARD PORTION OF BEAM

FRAME NO. 4

FIGURE 29 - PLASTIC HINGE FORMED IN FRAME NO. 4

FIGURE 30 - LEEWARD COLUMN AFTER TEST FRAME NO. 4

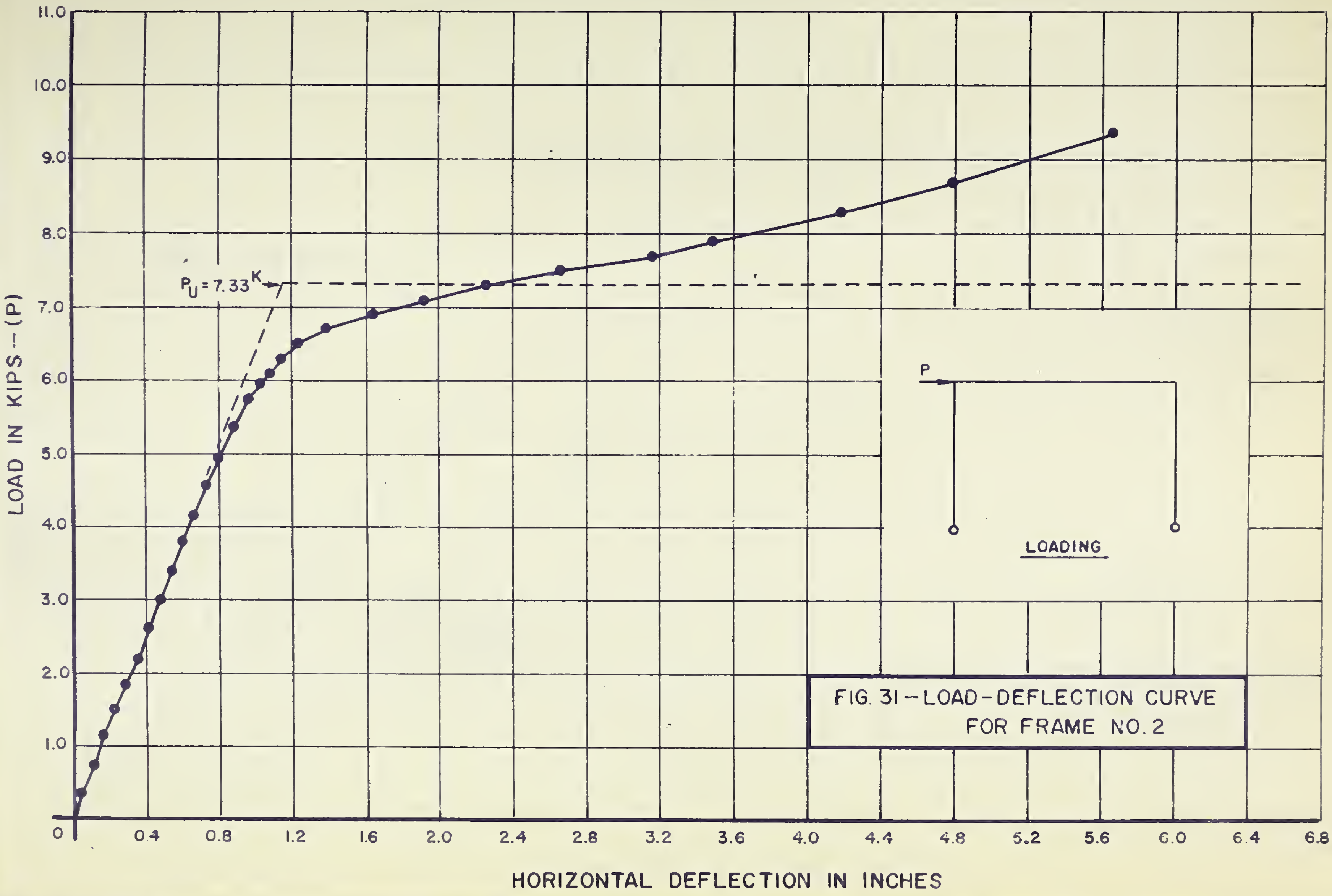


FIG. 31 — LOAD-DEFLECTION CURVE FOR FRAME NO. 2

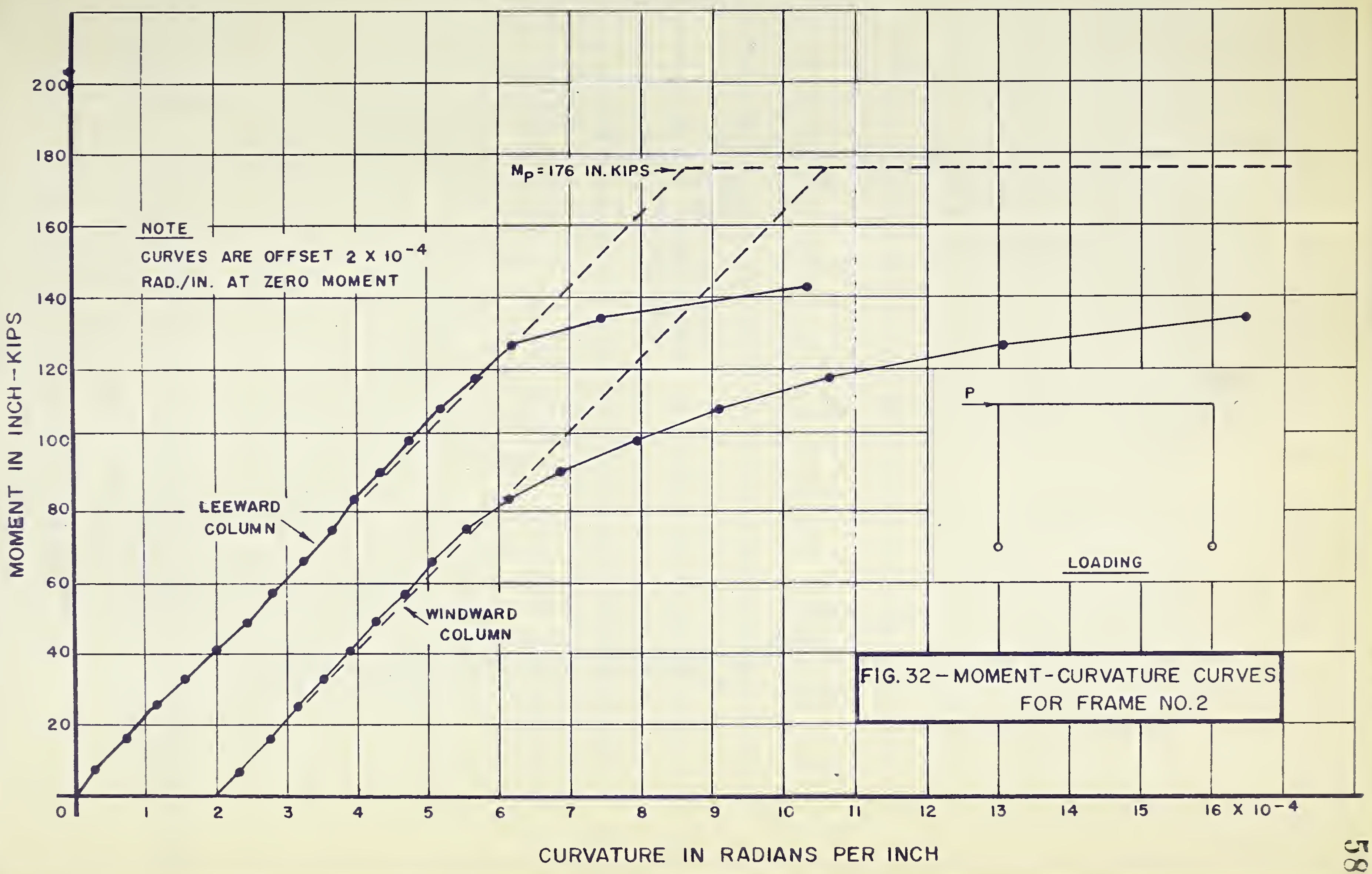


FIG. 32 – MOMENT-CURVATURE CURVES FOR FRAME NO. 2

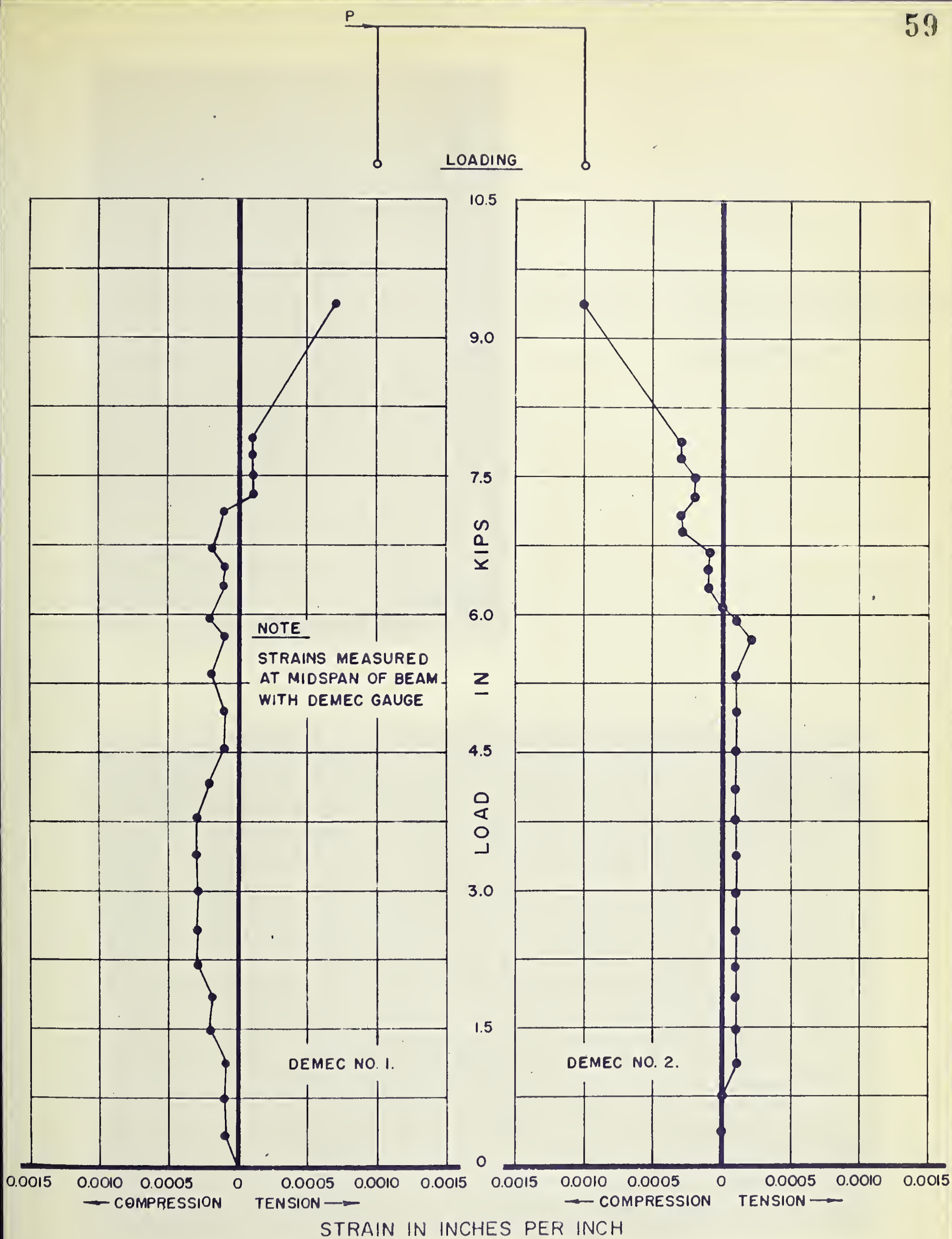


FIG. 33 -- LOAD - STRAIN CURVES FOR FRAME NO. 2

FIGURE 34 - PLASTIC HINGE FORMED IN FRAME NO. 2

FIGURE 35 - FRAME NO. 2 AFTER TEST

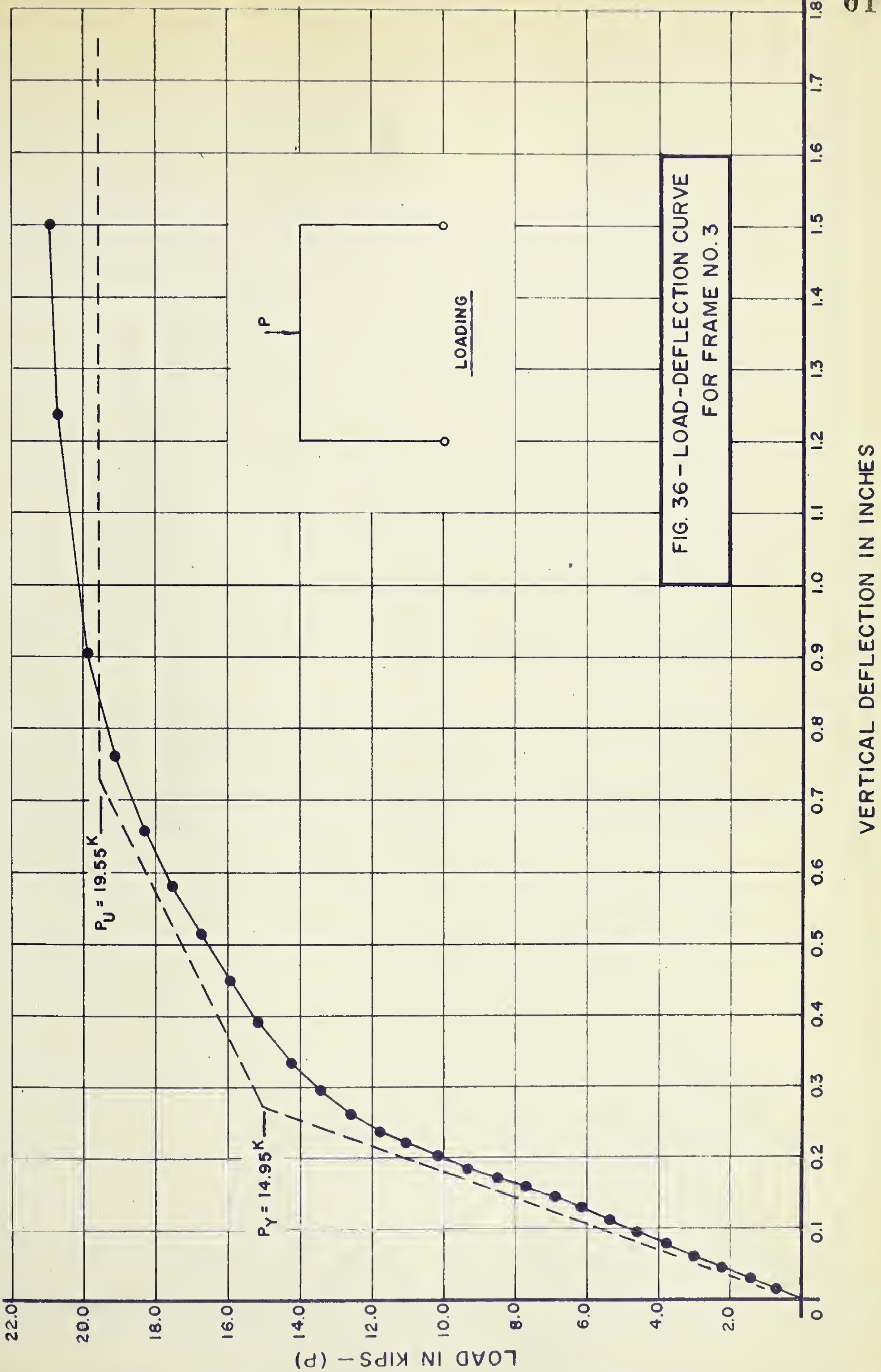


FIG. 36 - LOAD-DEFLECTION CURVE FOR FRAME NO. 3

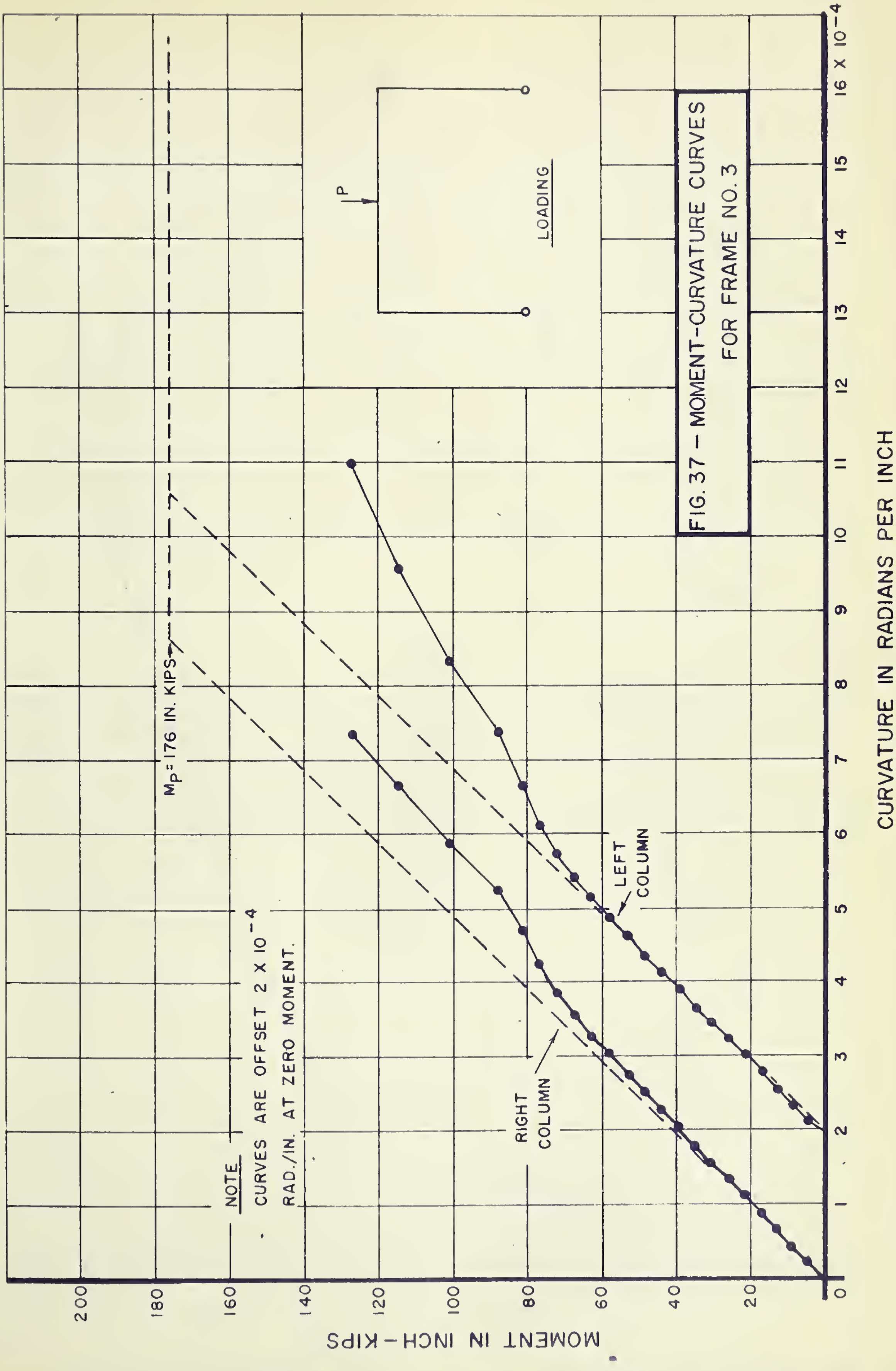


FIG. 37 – MOMENT-CURVATURE CURVES FOR FRAME NO. 3

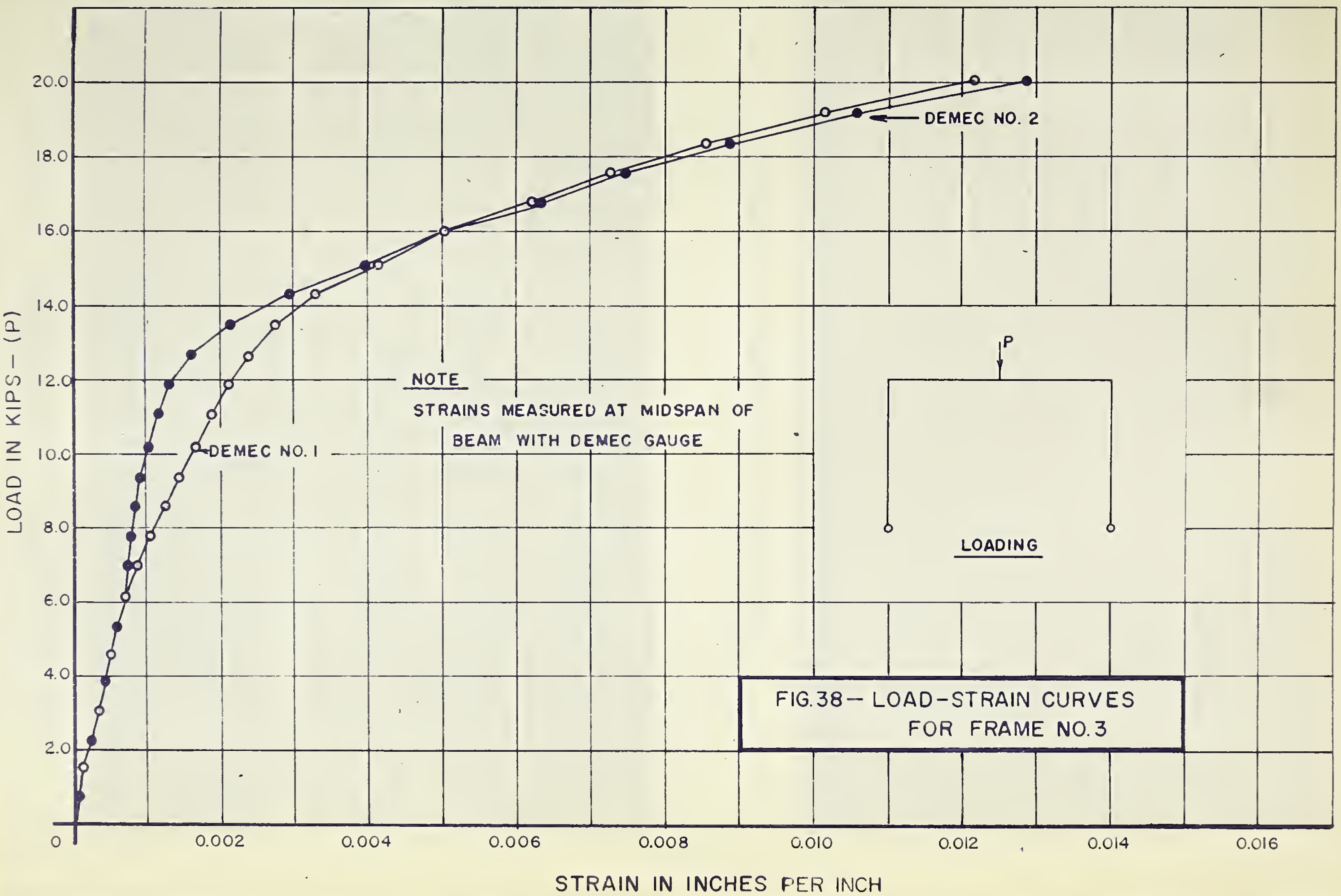


FIG. 38 — LOAD-STRAIN CURVES FOR FRAME NO. 3

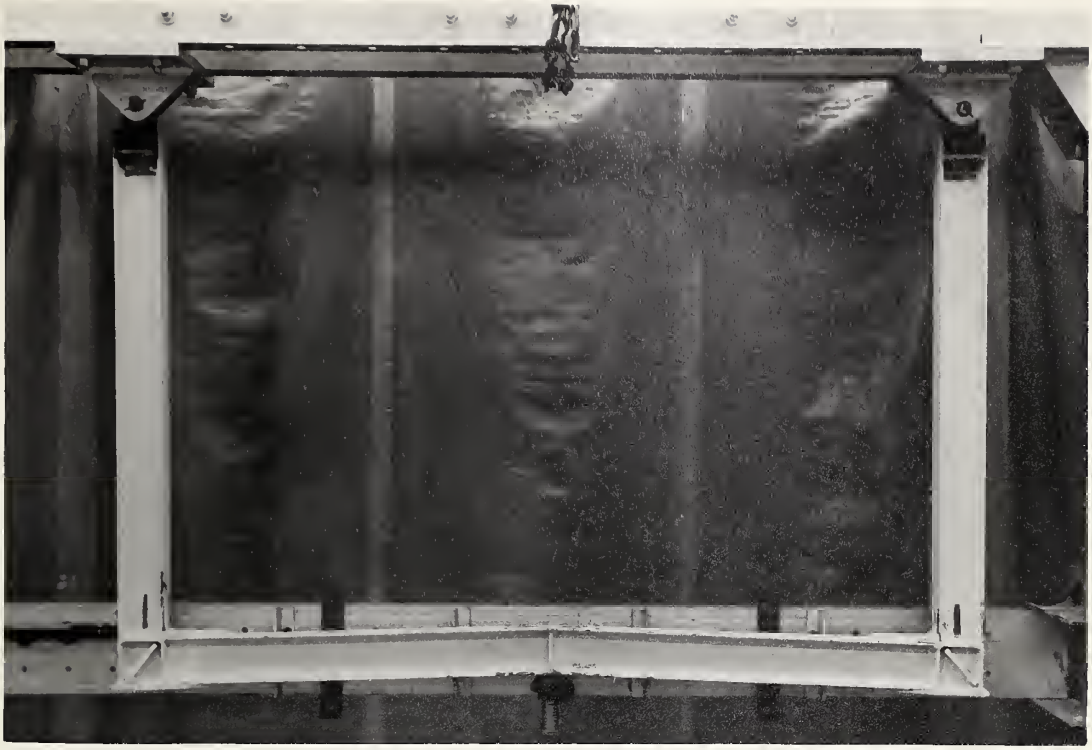


FIGURE 39 - FRAME NO. 3 AFTER TEST

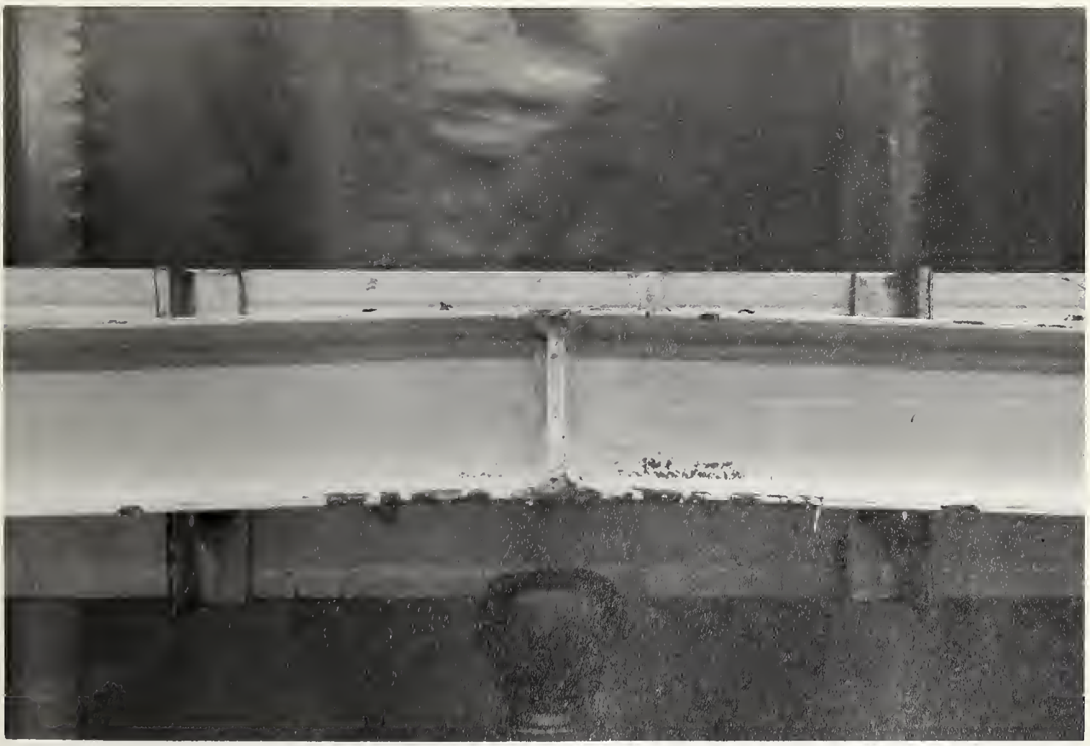


FIGURE 40 - PLASTIC HINGE AT MIDSPAN OF BEAM

FIGURE 41 - PLASTIC HINGE AT LEFT CORNER CONNECTION

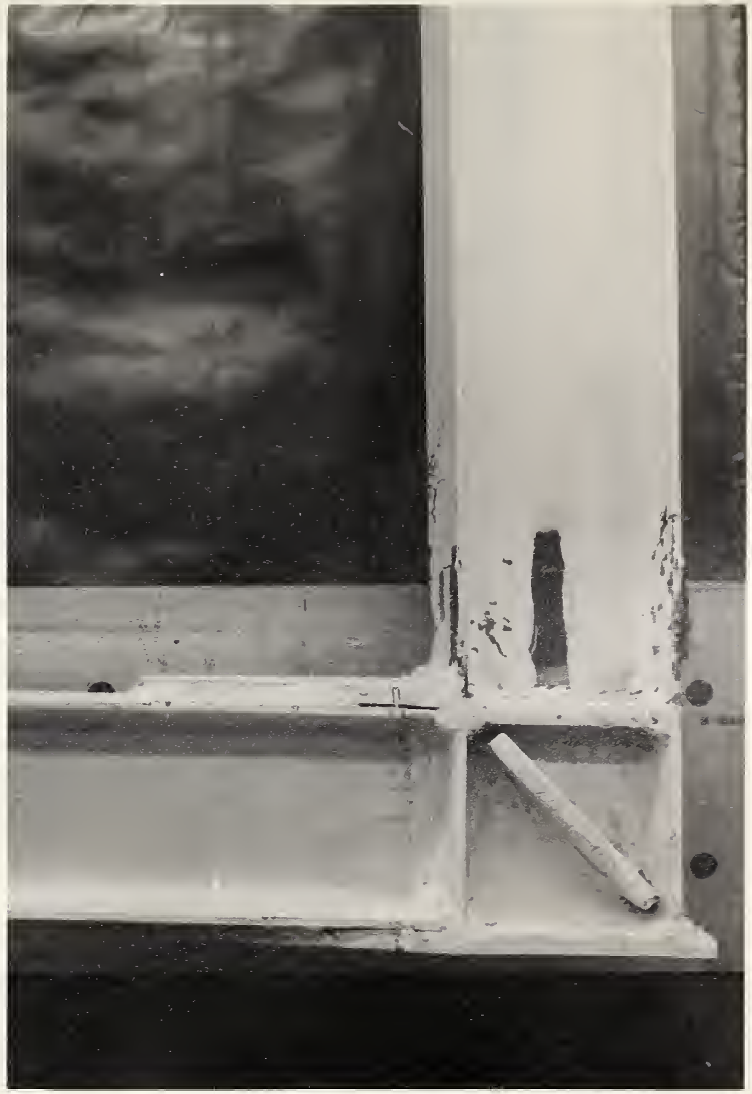


FIGURE 42 - PLASTIC HINGE AT RIGHT CORNER CONNECTION

DISCUSSION

Frame Nos 1 and 4

Results of tests on these frames are shown in Figures 15 to 30 inclusive. Both of the frames were subjected to combined horizontal and vertical loading of equal magnitude and were expected to behave in a similar manner; as a consequence, they are discussed together in order to compare results.

In this discussion frequent reference will be made to the windward column and to the leeward column. The windward column (shown to the viewer's left in Figure 11) refers to the column subjected to the horizontal load which simulates a wind loading. The leeward column is to the viewer's right in this figure.

Calculations made according to the simple plastic theory indicated that the frames should form a side-sway mechanism and collapse when the magnitude of the applied loads reached 7.33 kips. These calculations were made on the assumption that plastic hinges would occur at the corners of the line diagram formed by the centrelines of the frame members as was assumed in other theoretical calculations. This assumption normally would be made by a designer using the plastic design methods for the design of a steel frame similar to the ones used in these tests. According to Beedle[9], the effect of axial load on the plastic moment can be neglected with a

resulting error of less than 5 percent if the ratio of $\frac{P}{P_y}$ is less than 0.15 where P is the axial load on the member and P_y is the concentric load that would cause yielding of the entire column cross-section. In frames 1 and 4, the leeward column carried the greatest axial load, computed as 8.55 kips at theoretical ultimate load. P_y for the 4 I 9.5 for a yield stress of 44.0 k.s.i. is about 121.5 kips. Thus, the ratio $\frac{P}{P_y}$ for the leeward column was approximately 0.07 well below 0.15 so the effect of the axial load was neglected in the calculations of ultimate load. Beedle(9) recommends a maximum allowable shear force of Vmax = 18.0 wd where "w" is the web thickness and "d" is the section depth in order that the plastic moment be not reduced as a result of the effect of shearing force. For the 4 I 9.5 section this gives a maximum allowable shear value of approximately 23.4 kips. In Tests 1 and 4, the maximum theoretical shear in the columns at ultimate load was 3.67 kips and in the beam 8.55 kips, both well below the maximum value of 23.4 kips. Therefore shear was disregarded in the theoretical calculations of ultimate load. The new Canadian Standards Association Specification S16 for Steel Structures for Buildings contains the same recommendations concerning shear and axial load as have been outlined above.

Lateral buckling produced collapse of frame No. 1 before

the predicted ultimate load of 7.33 kips was reached. At a load of 7.0 kips, buckling of the windward half of the beam and of the leeward column was observed and further operation of the hydraulic rams increased the buckling deformations with no further increase in load so the test was halted. This test showed that the lateral support channels apparently were not rigid enough to withstand the imposed lateral forces so in subsequent tests, they were tied together at intervals by one-half by two inch straps and bolts as shown in Figure 5.

In test No. 4, the improved lateral support system prevented lateral buckling of the beam but the leeward column again buckled slightly. Buckling of the column was not observed until after the frame had reached a load in excess of its predicted ultimate load and apparently did not affect the load carrying capacity of the frame. The loading was stopped at 7.70 kips, about five percent in excess of the predicted ultimate load. At this point the load was still increasing slightly which was probably due to the occurrence of strain hardening at the sections of high curvature. The difference between the observed load carrying capacities exhibited by the two frames appears to be a direct result of the different lateral support provided. Tests at the University of California[8] on frames similar to those tested here showed an actual carrying capacity in excess of the

predicted capacity as did frame No. 4. The increased capacity in the California tests was attributed to the effect of strain hardening as was done here.

C.S.A. Specification S16 specifies that all plastic hinges except the last one to form shall be adequately braced to resist lateral and torsional displacement and that the laterally unsupported distance to adjacent support points need not be less than:

$$L_{cr} = (60-40 \frac{M}{M_p}) r_y$$

nor less than 35 r_y, where

L_{cr} is the laterally unsupported distance;

r_y is the radius of gyration of the member about its weak axis;

M is the lesser of the moments at the ends of the unbraced segment;

and M_p is the plastic moment.

r_y for the 4 I 9.5 sections used in the frames is 0.59 inches. Measurements taken on the sections compared quite closely with handbook values so tabulated values of the section properties have been used for all calculations. 35 r_y gives a minimum required spacing between lateral supports of twenty-one inches. The small projecting angles on the lateral support channels were spaced approximately eighteen inches apart which was less than the required minimum spacing and was sufficient to prevent lateral buckling of the

beam when the support channels did not move apart. According to the C.S.A. Specifications, the leeward column, which was subjected to the plastic moment at one end and was pin supported at the other, should have been laterally supported at a distance of 60 r_y or approximately thirty-six inches from its connection with the beam, where the plastic hinge formed. The need for the lateral support was shown by the fact that the leeward column buckled in both tests. Column instability apparently was not a factor in the buckling failure since the column had an L/r ratio in the plane of the frame of 29, well below the value of 60 permitted by the C.S.A. S16 for a pin-ended column with a $\frac{P}{P_y}$ ratio less than 0.15.

Load vs. horizontal deflection curves for frames 1 and 4 are shown in Figures 15 and 23 respectively. Both frames followed the theoretical deflection curve quite closely for the lower loads and frame No. 4 followed the theoretical curve quite closely throughout the entire loading range. The curve for frame No. 1, which failed to reach its predicted ultimate load, fell slightly below the theoretical curve in the higher load range but displayed the same general shape as the theoretical curve. The observed curve for frame No. 4 shows that the loads were still increasing slightly when the test was stopped. The deflections, however, were increasing rapidly and the frame would have no longer been

useful as a structural component. The one kink in the curve may be due to an error in taking deflection readings.

Load vs. vertical deflection curves for the frames are shown in Figures 16 and 24. Both observed curves again displayed the general shape of the theoretical curves. The two observed curves are very nearly identical up to a load of 5.5 kips but beyond this load, the curve for frame No. 1 falls below the curve for frame No. 4. This phenomenon probably was caused by the lateral buckling of the beam in the first test.

Moment vs. curvature curves for frames 1 and 4 are shown in Figures 17 and 25 respectively. Observed curves are compared with the idealized moment-curvature curve for the 4 I 9.5 section which is shown as two straight lines. The idealized curve assumed that curvature is proportional to the applied moment up until the plastic moment value is reached after which curvature is assumed to increase with no increase in the applied moment. The observed curves represent the moment-curvature relationship at the strain gauge locations near the top of each column. Curvatures were determined using the data obtained from the four flange gauges at each of these locations. Certain assumptions concerning the magnitude of the frame reactions had to be made before the curves could be drawn. The value of the curves is therefore limited by the accuracy of the assumptions made. Instrumenta-

tion was not included in the test apparatus to measure the reactions at the column bases so they had to be calculated for each load increment before the moments acting at the strain gauges could be determined. As a consequence, the moments used in plotting the moment curvature curves are not observed values but computed values. Calculations for the theoretical moment - load relationships are shown in Appendix D. For loads less than 5.82 kips, which was the load calculated to form the first plastic hinge at the top of the leeward column, the reactions were assumed to be equal to those determined by an elastic analysis of the frame. For loads of 5.82 kips, the calculated horizontal reaction at the base of the leeward column was 3.67 kips and was assumed not to increase beyond this value after the plastic hinge had formed. After the applied loads reached 5.82 kips, the increase in horizontal load was assumed to be taken entirely by the horizontal reactions at the windward column while the horizontal reaction at the leeward column remained constant. At the calculated ultimate load of 7.33 kips the horizontal reaction at the windward column also reached 3.67 kips as the collapse mechanism was formed. The maximum value of the horizontal reactions was then assumed to be 3.67 kips although strain hardening might increase their magnitudes.

The assumed plastic hinge locations did not coincide

with the strain gauge locations and as a result, the moment-curvature curves appear to show that the theoretical plastic moment capacity of the 4 I 9.5 section was not reached in either of the tests. As has been mentioned previously, the hinges were assumed to form at the corners of the line diagram representing the centrelines of the frame members and the horizontal reactions calculated to form the plastic hinges there were 3.67 kips. The assumed maximum horizontal reactions of 3.67 kips produce a maximum moment at the strain gauge locations, shown in Figure 9, of 161.5 inch-kips which is the maximum moment shown on the observed moment-curvature curves. If the hinges had been assumed to form at the strain gauges, the moment values would have been increased slightly and the observed curves would have indicated that the full plastic moment value for the section had been reached.

The moment-curvature relationships for frame No. 1 show poor correlation with the theoretical curves, probably because of the lateral buckling that occurred. Strain gauge readings were discontinued at a load of 6200 lbs. so the curve for the windward column did not reach the maximum moment value. When the readings were discontinued however, the observed curve had fallen well away from the theoretical curve indicating that the reaction for the windward column might have been somewhat higher than the assumed value. The curves for frame No. 4 showed better correlation with the

theoretical curves although they fell away from the theoretical curves at the higher moment values, again indicating that the horizontal column reactions might have been higher than assumed. A kink in the windward column curves for both frames is noticeable at a moment value of approximately ninety-five inch kips. This was the theoretical moment at the gauges on the windward column when the plastic hinge was assumed to form at the top of the leeward column and the break apparently shows that the assumption concerning the horizontal reactions at this load was not entirely correct. The kink is not very noticeable in the curve for frame No. 4 indicating that the assumed action agreed closely with the actual.

Load-strain curves for frame No. 4 are shown in Figure 26. The readings on demec No. 1 increased more rapidly than on demec No. 2 indicating that the beam was bending slightly about its weak axis at midspan. The lateral movement, however, was so slight that it was not visible to the eye and apparently didn't affect the load carrying capacity of the frame.

Frames 1 and 4 are shown after testing in Figures 18 and 27 respectively. The final shape of the frames was similar as can be seen in the pictures. It is interesting to note that the windward portion of the beam showed extensive yielding as evidenced by its curvature. The curvature

of the two beams can be seen clearly in Figures 19 and 28. The windward portion of the beam was subjected to a fairly flat moment gradient at ultimate load with a moment equal to the plastic moment acting at the column connection and a moment equal to three-quarters of the plastic moment acting at the midspan of the beam. As a result of the flat moment gradient, yielding spread over most of the windward portion of the beam while strain hardening increased the moment resistance where yielding first occurred near the column connection.

The buckled beam of frame No. 1 is shown in Figure 20. Lateral buckling occurred in the windward portion of the beam which was, as mentioned previously, subjected to high moments. Improved lateral support prevented a similar occurrence in frame No. 4. Plastic hinges formed near the beam to leeward column connections of the two frames are shown in Figures 21 and 29. Figures 22 and 30 are views of the leeward columns. As was previously mentioned, the columns buckled in both tests and the buckling is shown clearly in both figures.

Whitewash applied to the frames to show yielding at the plastic hinges did not flake off appreciably during the tests. Evidence of this fact is readily seen in the pictures which show the whitewash still virtually untouched in most cases. There was very little mill-scale on the frames, which pro-

bably explains the fact that the whitewash did not flake off.

Frame No. 2

Test results for frame No. 2 are shown in Figures 31 to 35 inclusive. This frame was subjected to a single load applied horizontally at the top of the windward column. The predicted collapse load for this condition was 7.33 kips. Axial load in the columns at the predicted ultimate load of 7.33 kips was calculated to be approximately 4.9 kips which gave a $\frac{P}{P_y}$ ratio for the 4 I 9.5 section of $\frac{4.9}{121.5}$ or 0.04. This was again well below the $\frac{P}{P_y}$ value of 0.15 indicating the plastic moment capacity should not be affected by the axial load. Axial load was therefore neglected in the theoretical calculations. The shear forces of 3.67 kips in the columns and 4.9 kips in the beam at the predicted ultimate load were well below the value of 23.4 kips in the 4 I 9.5 section, above which shear would affect plastic moment capacity, so the effect of shear was also neglected in the theoretical calculations.

The load vs. horizontal deflection curve for the frame is shown in Figure 31. As can be seen in this figure, the load on the frame was well in excess of the theoretical ultimate load when the test was stopped. The final load was 9.35 kips, twenty-seven percent greater than the theoretical ultimate. When the test was stopped, the load was still increasing, as indicated by the load-deflection curve. This phenomenom

can be attributed to strain hardening at the plastic hinges.

Moment-Curvature relationships at the strain gauge locations on the two columns are shown in Figure 32. Bending moments were calculated assuming that the horizontal reactions were each equal to one-half of the applied horizontal load. Strain gauge readings were discontinued before the end of the test so the complete moment-curvature curves could not be shown. Both curves, however, showed curvatures to be increasing rapidly with small moment increases when the strain gauge readings were stopped. It is also evident that these large curvatures were occurring at moment values well below the predicted moment capacity. Residual stresses are known to have this effect on the moment-curvature relationship[9] although the plastic hinge will eventually reach its full moment capacity at somewhat higher curvatures than those predicted by the idealized moment-curvature curve. If the strain gauge readings had been continued in this test, the observed curve may have reached the predicted moment capacity but curvatures would have been a great deal larger than predicted.

No evidence of lateral buckling was observed during the test, although the load-strain curves shown in Figure 33 indicate that the beam was bending laterally slightly when the test was stopped. Demec No. 1 indicated increasing tensile strain on one edge of the flange while Demec No. 2 indicated increasing compressive strain on the other edge of the flange

at the 9.35 kip load. The bending was slight, however, and apparently did not affect the load carrying capacity of the frame.

One of the plastic hinges formed during the test is shown in Figure 34. Figure 35, showing the frame after the test, gives a view of the side-sway mechanism formed.

Form No. 3

Results of the test on this frame are shown in Figures 36 to 42 inclusive. The frame was loaded with a single load applied vertically at the midspan of the beam, and was expected to collapse by forming a beam mechanism at a predicted load of 19.56 kips. The axial load in the columns at the predicted ultimate load was approximately 9.8 kips, giving a $\frac{P}{P_y}$ value for the 4 I 9.5 section of $\frac{9.8}{121.5}$ or about 0.08. Axial load was therefore neglected in making the ultimate load calculations. Shear forces of 3.67 kips in the columns and 9.8 kips in the beam were well below the shear value of 23.4 kips in the 4 I 9.5 section so shear was also disregarded in making the theoretical calculations.

The load vs. vertical deflection curve for the frame is shown in Figure 36. The observed curve compares quite favorably with the theoretical curve over the entire loading range. The test was stopped at a load of 21.0 kips, about seven percent in excess of the predicted ultimate load. Loading was stopped at this load to prevent damage to the hydraulic ram

which was already loaded beyond its rated capacity of 20 kips. The load-deflection curve, however, indicates that the frame was very near its ultimate capacity when the test was stopped.

Moment-curvature relationships for the frame are shown in Figure 37. No horizontal load was applied in this test so the columns are referred to as the left and right columns rather than the windward and leeward columns. Left and right refer to the columns as seen by the viewer in Figure 13. In order to plot these curves, it was again necessary to make assumptions concerning the horizontal reactions before the moments at the strain gauges could be determined. Moment calculations are shown in Appendix D. The first plastic hinge was assumed to form at the midspan of the beam at a load of 14.95 kips. For loads less than this value, the horizontal column reactions at each load increment were assumed to be equal to those determined by an elastic analysis of the frame and moments at the strain gauges were calculated using these reactions. For loads larger than 14.95 kips, the horizontal reactions were calculated assuming a moment equal to the theoretical plastic moment for the 4 I 9.5 section acting at the midspan of the beam. The moment-curvature curves are incomplete because strain gauge readings were discontinued before the end of the test. The observed curves, however, were curving away from the theoretical curve before the readings were discontinued, possibly due to the influence of residual stresses. Both columns displayed practically identical moment-

curvature relationships up to a moment of about eighty-five foot kips where sharp breaks occurred in both curves. The breaks in the curves occurred when the plastic hinge was assumed to form in the beam indicating that the moment acting at the midspan of the beam was somewhat larger than assumed. If a larger moment had been assumed at the midspan of the beam, the calculated horizontal reactions would have been lower, thereby decreasing the calculated moment at the strain gauges and the final portions of the moment curvature curves would have been flattened to correspond with the initial portion of the curves.

The moment-curvature relationships obtained for the four frames were, in general, not too satisfactory. This was partly due to the assumptions that had to be made before the curves could be plotted. The results, however, were probably affected by other factors as well. The moment gradients were quite steep at the locations where curvatures were measured in these tests. Had it been possible to measure the curvatures at some section of the frame where the moment gradient was flat, that is at a section of constant moment, the results might have been better. For the loading conditions employed, however, no sections of the frames were subjected to a constant moment. The vertical reactions would also introduce bending moments at the strain gauges as the tops of the columns deflected horizontally. These bending moments were neglected

in making the moment-curvature calculations. However, even if the moments due to the vertical reactions had been taken into account, the maximum moment acting at the plastic hinge locations would have still been assumed to be equal to the plastic moment capacity for the 4 I 9.5 section. The assumed maximum horizontal reactions would then have been changed accordingly in order that the theoretical plastic moment capacity was not exceeded at any section of the frame. The net result would be that the moment-curvature curves would not be changed significantly and the maximum calculated moment at the strain gauges would still be somewhat smaller than the plastic moment capacity of the 4 I 9.5 section. Had it been possible to measure the reactions, the effect of the vertical reactions on the bending moments as the frames deflected horizontally would have had to be taken into account.

The load vs. strain curves obtained from the demec gauge readings taken at the midspan of the beam are shown in Figure 38. The beam apparently was bending slightly about its weak axis during the test. The bending was almost negligible, however, and no lateral buckling occurred. It is interesting to note that the strain began increasing rapidly at a load of approximately 13 kips. The plastic hinge was predicted to form at the midspan of the beam at a load of 14.95 kips and the strains recored by the demec gauge show evidence of the

formation of the hinge at a load close to the predicted value.

Figure 39 gives a view of the frame after the test was completed. The beam mechanism formed as predicted, as is clearly illustrated in this picture. The plastic hinge formed at the midspan of the beam is shown in Figure 40 and the plastic hinges formed at the beam to column connections are shown in Figures 41 and 42. In the latter two cases, it is significant to note that the connections themselves have shown no signs of distress due to the imposed loading. This behavior was also observed in the other tests as no sign of failure was detected in any of the connections. These observations indicated that relatively simple connections, when properly stiffened to prevent damage due to high shear stresses, will not fail prematurely before the ultimate strength of the frame is developed.

Coupon Tests

Coupons tested at the different strain rates showed marked differences in the values of lower yield stress obtained. The coupons loaded in increments gave lower yield stresses of 43.6 k.s.i. and 44.4 k.s.i., whereas, the coupons loaded at the maximum specified A.S.T.M. strain rate of 1/16 inch per minute per inch of gauge length gave lower yield stresses of 50.7 k.s.i. and 52.0 k.s.i. The loading used on the former coupons more closely simulated the loading on the frames in that the load was applied to the frames in increments. There-

fore the average yield stress determined by the slow tests was used in ultimate load calculations for the frames. Coupons were cut from the web of the section which would be expected to have a slightly lower yield stress than the flanges since the flanges were rolled thinner. Differences, however, would be small and were neglected in the theoretical calculations.

Tall[10] has reported the results of tests at Lehigh University showing the influence of strain rate on the yield strength of steel. He reports that yield stresses found at normally accepted mill testing speeds can be thirteen to eighteen percent greater than what he refers to as the "static yield stress" or the yield stress found at zero strain rate. The "static yield stress" is considered the logical yield stress to be used since most structural loads are considered to be static. Yield stresses determined in the present tests using the A.S.T.M. strain rate which would be used in mill tests, were approximately sixteen percent greater than those obtained with the incremental loading. This would indicate that the incremental loading gave a yield stress value close to that which Tall has defined as the "static yield stress".

CONCLUSIONS

Conclusions based on the results of this investigation are summarized as follows:

1. Three of the test frames exhibited ultimate load carrying capacities greater than predicted by the simple plastic theory. The excess carrying capacity might be attributed to the effect of strain hardening at the plastic hinges. The remaining frame, which was the first one tested, failed at a load slightly smaller than its predicted capacity. The load carrying capacity of the frame was restricted by lateral buckling of the beam which did not have sufficient lateral support.
2. The load-deflection curve for a frame can be predicted quite accurately over the entire loading range using analytical methods.
3. Derived moment-curvature curves for the frames in general showed poor agreement with the idealized moment-curvature curves. The poor agreement is attributed largely to the assumptions that had to be made in order to plot the derived curves and to the fact that a fairly steep moment gradient existed at the sections of the frames where curvatures were measured.

4. None of the corner connections of the frames showed any signs of distress during the tests indicating that relatively simple connections, if properly stiffened, will develop the full plastic strength of the adjoining members.
5. Results of coupon tests conducted to determine material properties indicated that the value of the yield strength observed for a coupon test increased with increasing strain rate.
6. The lateral support system, as originally designed, did not provide adequate lateral support to prevent buckling of the beam in the first test. Sufficient lateral support was provided in subsequent tests after improvements were made in the original design.
7. The loading system functioned as it was designed to, notwithstanding the inadequacy of the lateral support system in the first test. It appears that the loading system is satisfactory for the type of tests conducted.

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APPENDIX A

DETAILS OF LOADING FRAME

Details of the loading frame designed for these tests are shown in this section.

The assembly drawing of the frame shown in Figure A1 gives the relative positions of the members which are detailed in Figures A2 to A5 inclusive. The beam sections, as shown in Figure A1, can be positioned at a maximum distance of ten feet between centrelines giving a clear height of nine feet. Bolted connections between the column and beam sections permit the beams to be moved to different positions and the clear height between beams can therefore be reduced if desired. The ten foot distance between column centrelines allows a clear span between columns of nine feet. The hinge supports and roller plate are bolted to the beam sections and can be positioned as desired.

The frame, with the beams positioned as shown in Figure A1, was designed for a concentrated vertical load of thirty kips acting at the midspan of the beam together with a concentrated horizontal load of ten kips acting at the midheight of the column. Various reaction components were possible for this loading and several different situations were analyzed in making the design. It is realized that loads may be applied at points on the frame other than those used

in the original analysis and persons planning to use the frame for future tests should analyze the frame for adequacy under their particular loading condition. Properties of the frame sections are given below as an aid to anyone wishing to make such an analysis of the frame.

Column Section - (See Figure A2)

Main member - 12 WF 40 with 13/16 inch diameter holes in one flange.

Moment of Inertia - 278.3 $inch^4$

Section Modulus - 43.2 $inch^3$

Allowable Moment - 72 foot-kips (at maximum fibre stress of 20 k.s.i.)

Beam Section - (See Figure A3)

Main Member - 2-12 channels 20.7 with 13/16 inch diameter holes in one flange.

Moment of Inertia - 224.8 $inch^4$

Section Modulus - 34.8 $inch^3$

Allowable Moment - 58 foot-kips (at maximum fibre stress of 20 k.s.i.)

Section properties given above are based on the net area of the sections after hole areas have been deducted.

The bolted beam to column connections are capable of withstanding a moment of 187 foot-kips if the high strength bolts in the connections are tensioned up to their proof loads. This moment is well in excess of that allowable on either the beam or column sections.

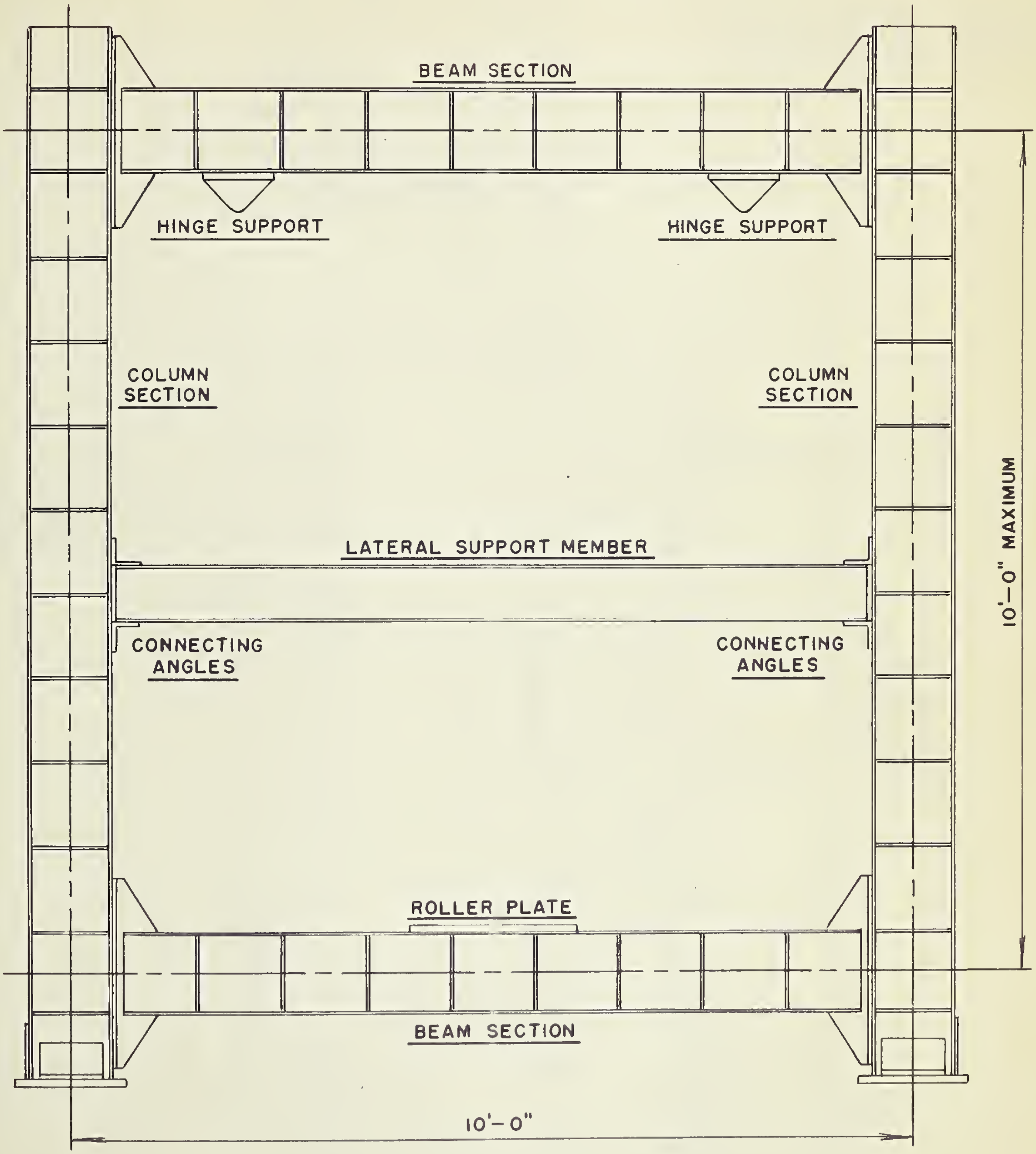


FIG. A1 – ASSEMBLY DRAWING OF LOADING FRAME

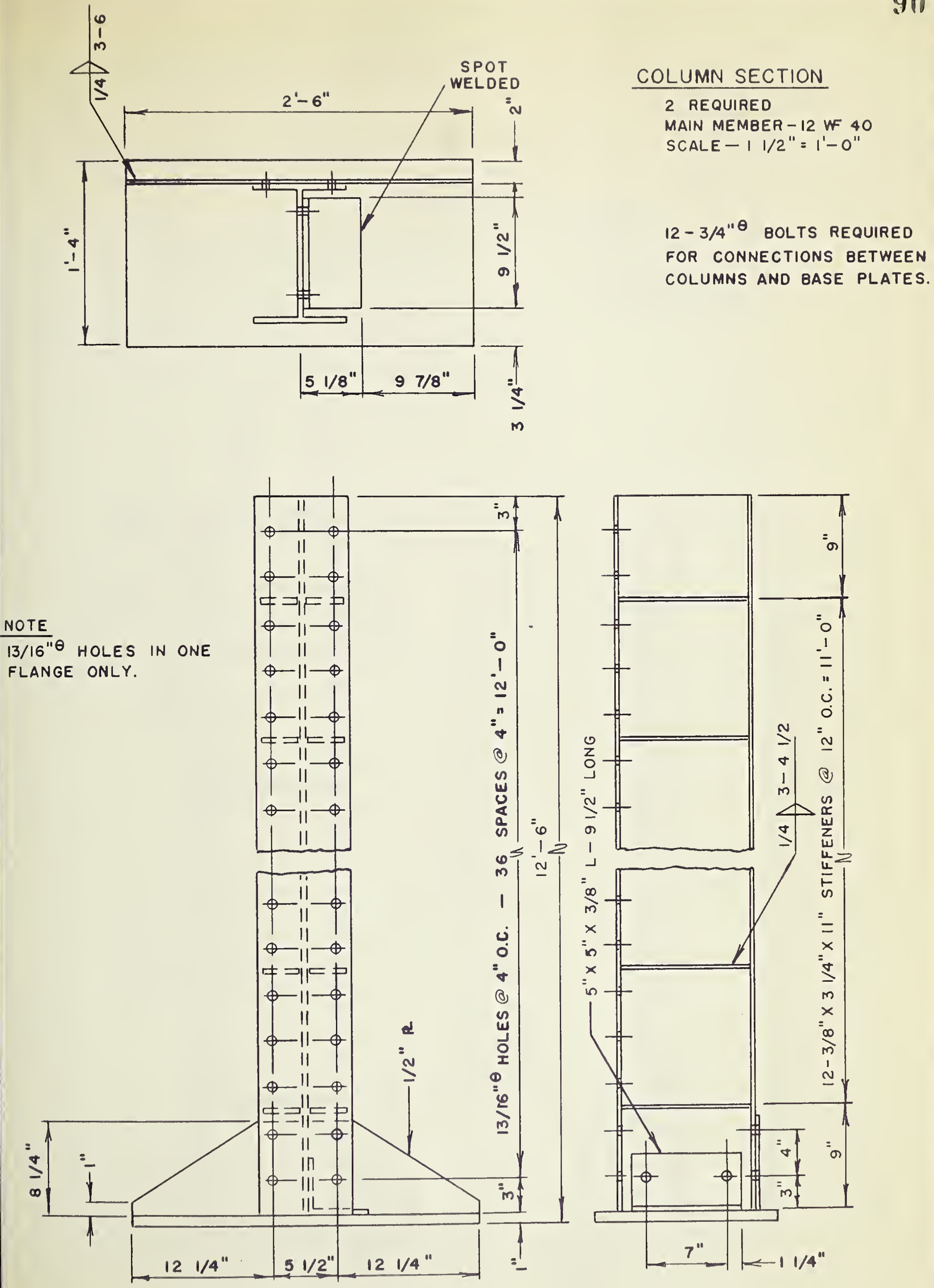


FIG. A2-DETAILS OF LOADING FRAME

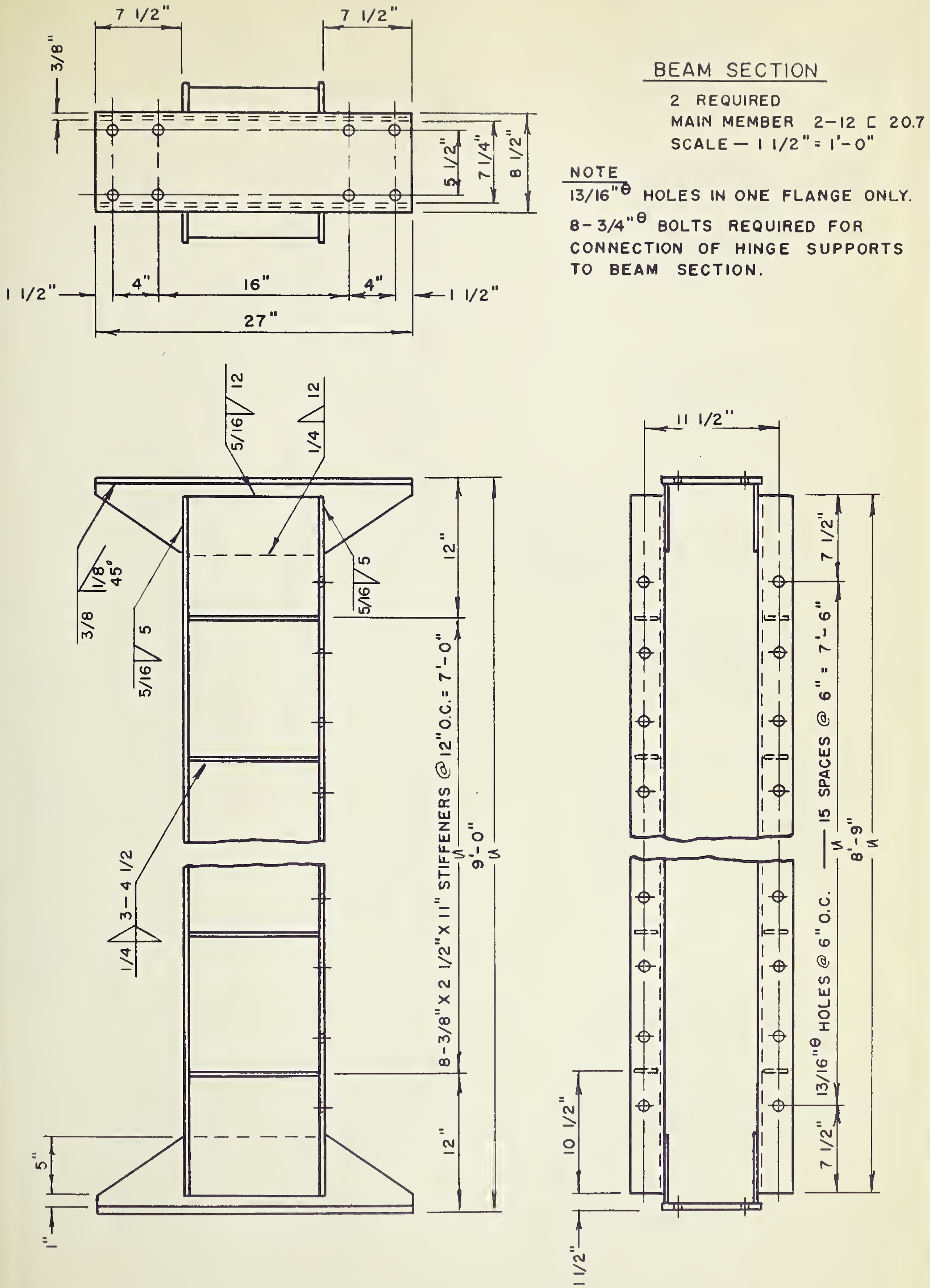


FIG. A3—DETAILS OF LOADING FRAME

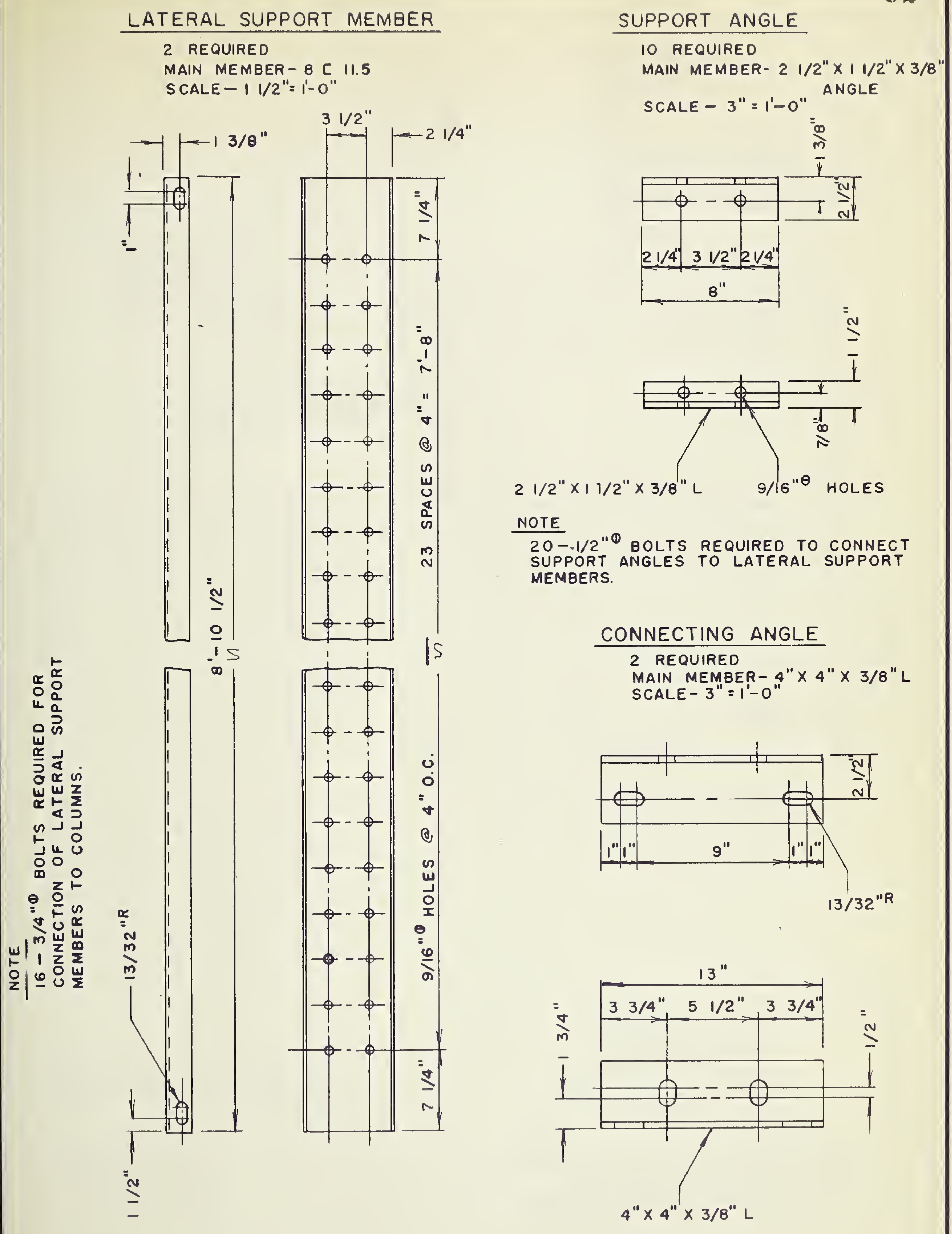


FIG. A4—DETAILS OF LOADING FRAME

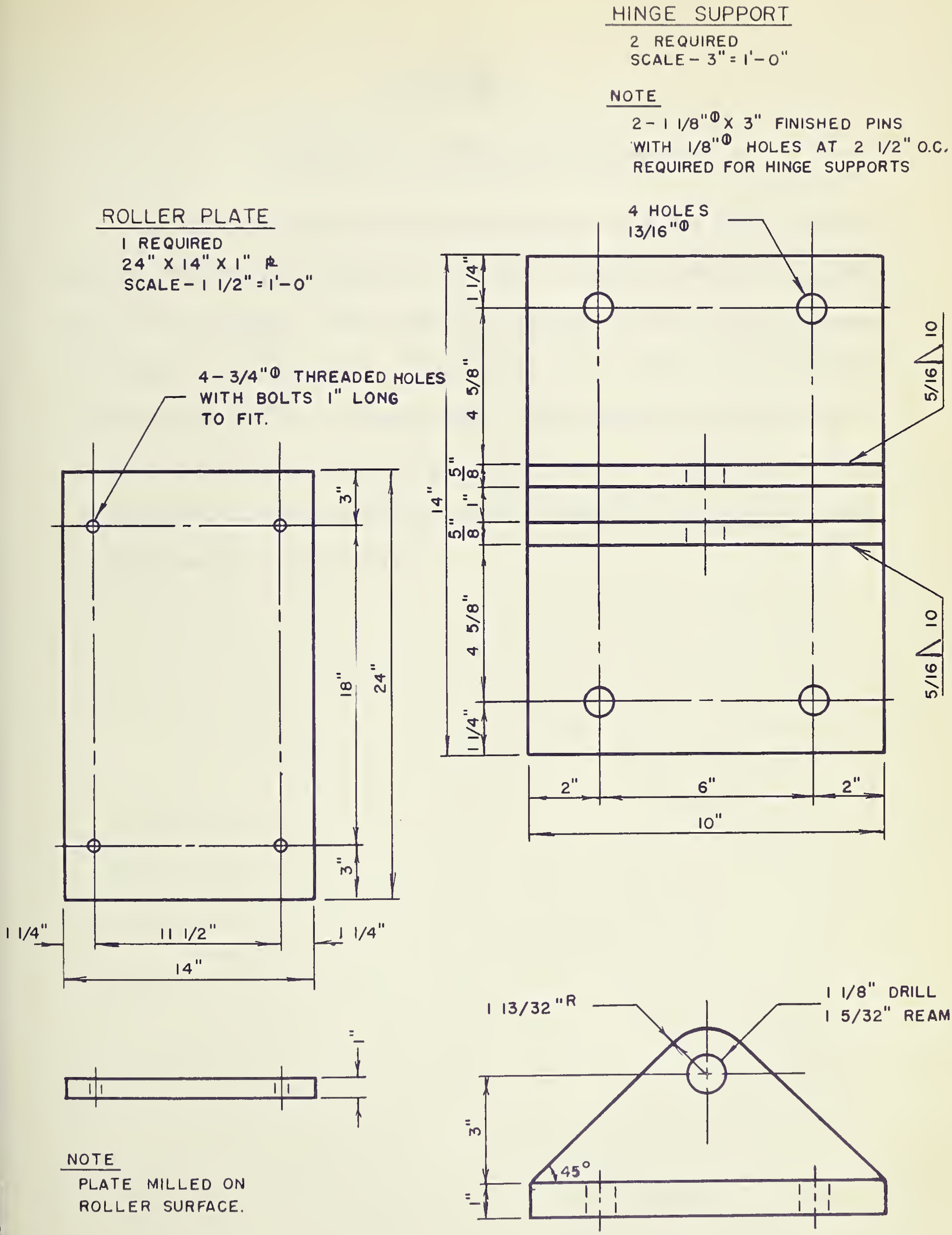


FIG. A5 – DETAILS OF LOADING FRAME

APPENDIX B

DETAILS OF ROLLER MECHANISM

Details of the roller mechanism used in the tests to allow horizontal movement of the vertical loads are given in this section. An assembly drawing of the roller parts is shown in Figure B1. The individual parts are detailed in Figures B2 to B6 inclusive. The design load for the roller mechanism is 20 kips which is the capacity of the "Blackhawk RC-161" hydraulic ram that was mounted on the mechanism for these tests.

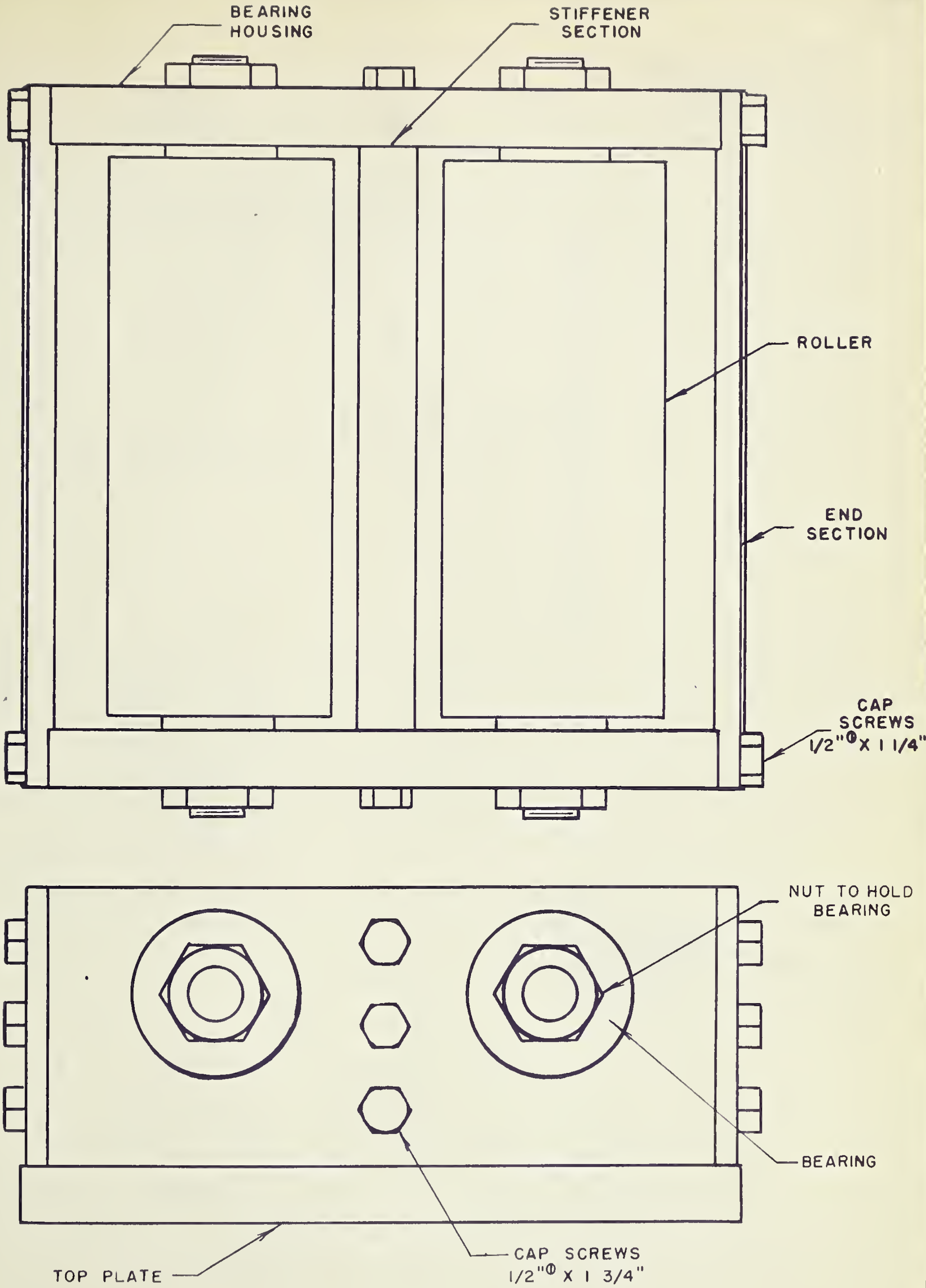
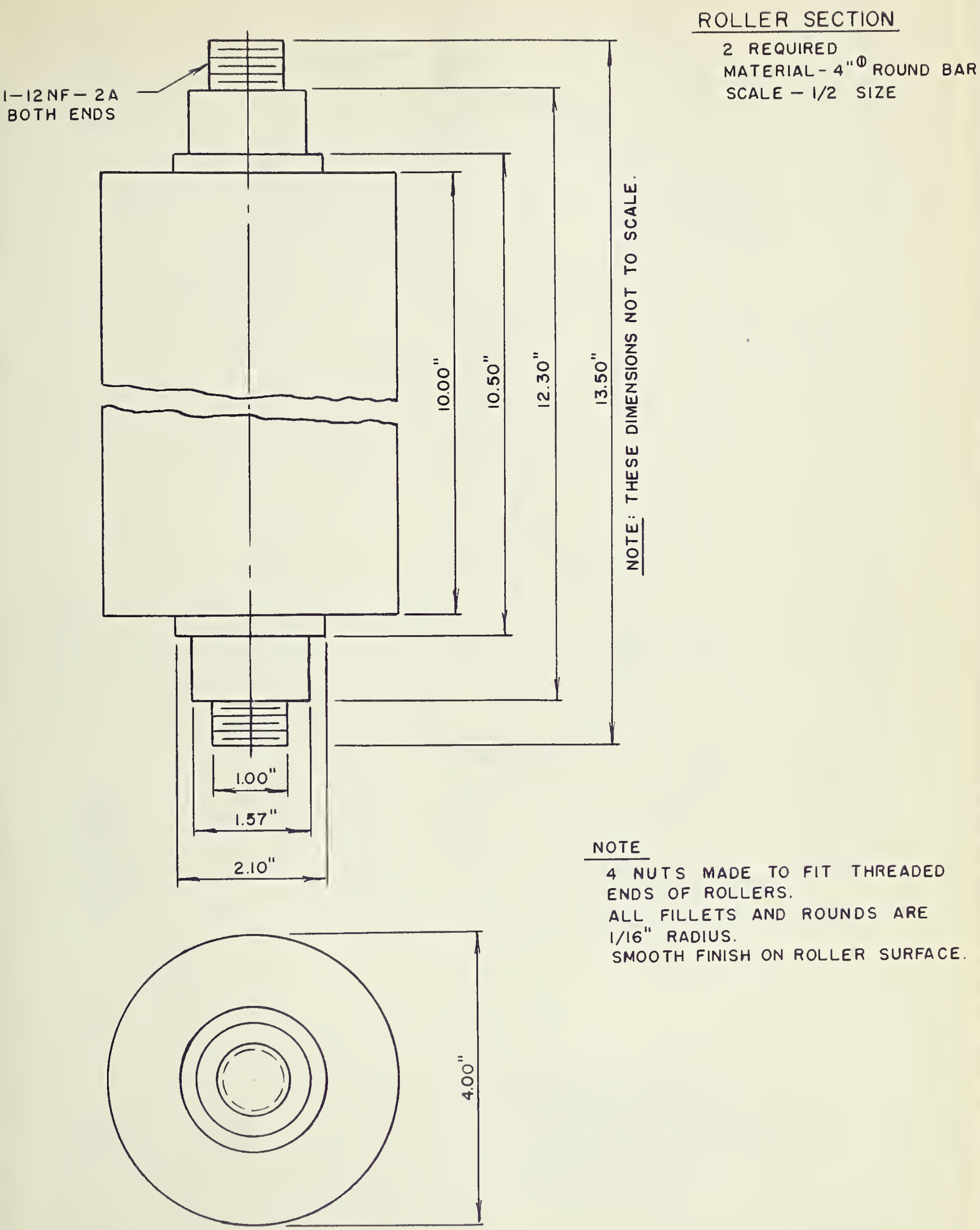


FIG. B1—ASSEMBLY DRAWING OF ROLLER MECHANISM



NOTE

4 NUTS MADE TO FIT THREADED ENDS OF ROLLERS.
ALL FILLETS AND ROUNDS ARE 1/16" RADIUS.
SMOOTH FINISH ON ROLLER SURFACE.

FIG. B2 - DETAILS OF ROLLER MECHANISM

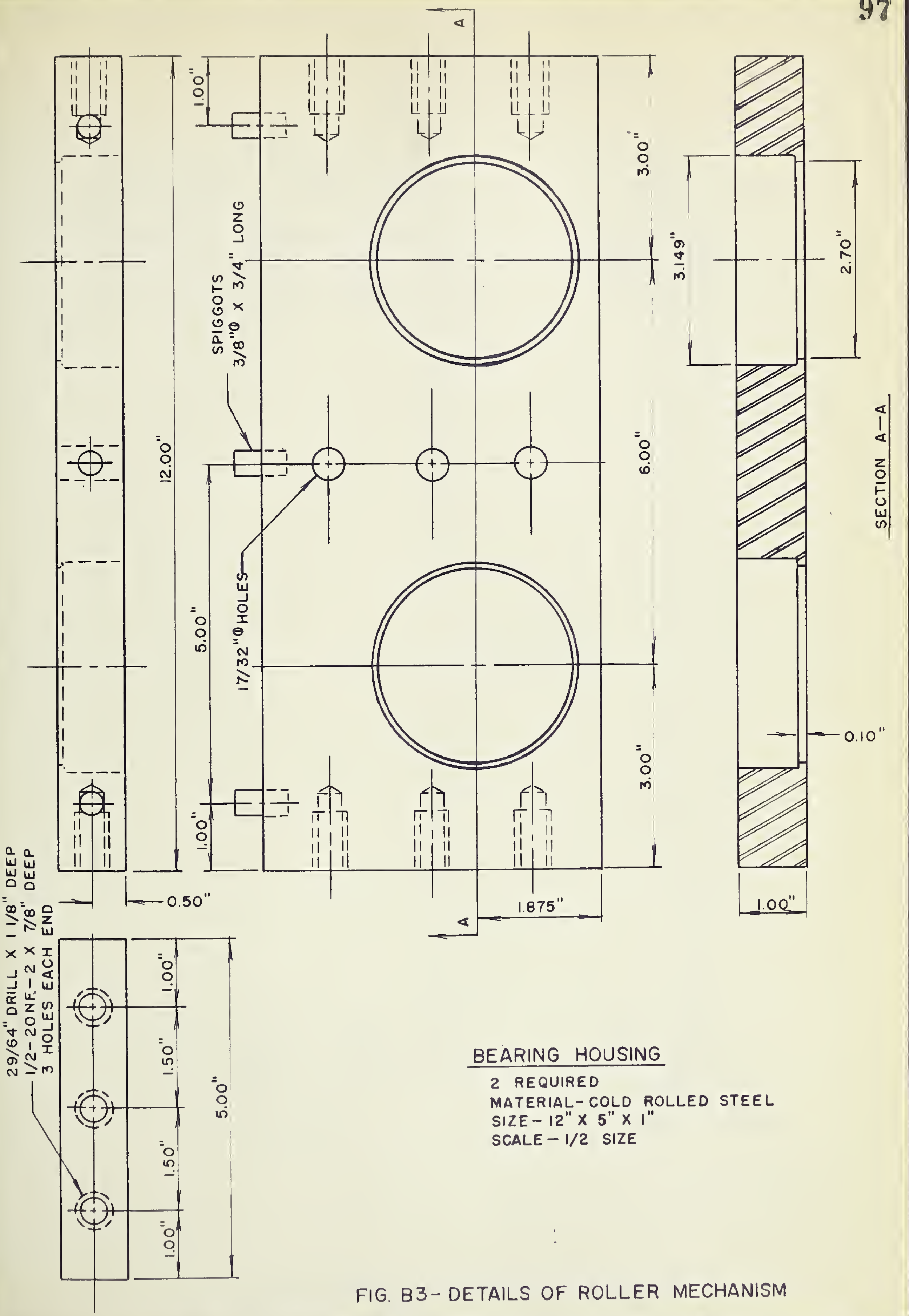


FIG. B3- DETAILS OF ROLLER MECHANISM

END SECTION

2 REQUIRED
MATERIAL—COLD ROLLED STEEL
SIZE - 12 1/2" X 5" X 1/2"
SCALE— 1/2 SIZE

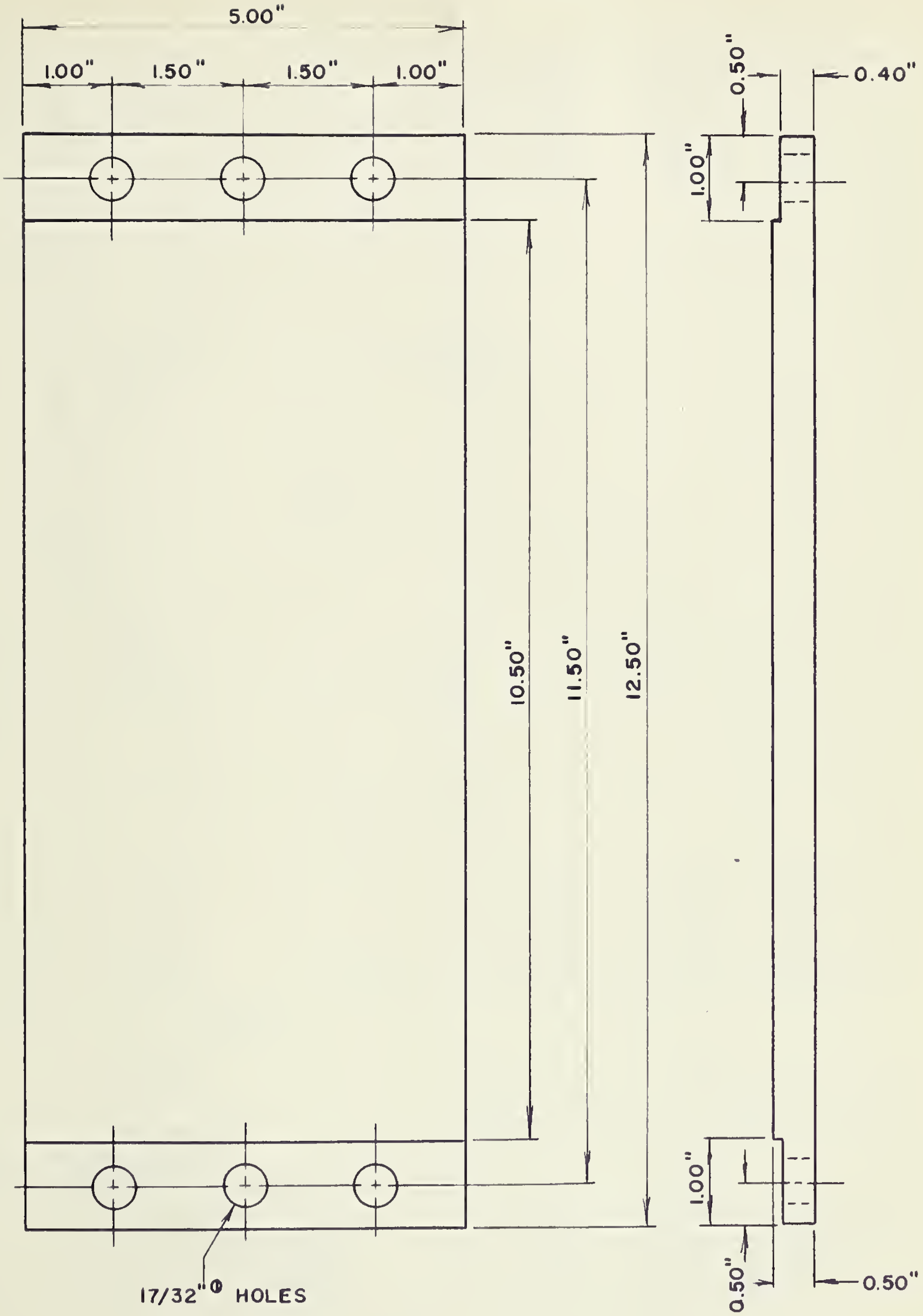
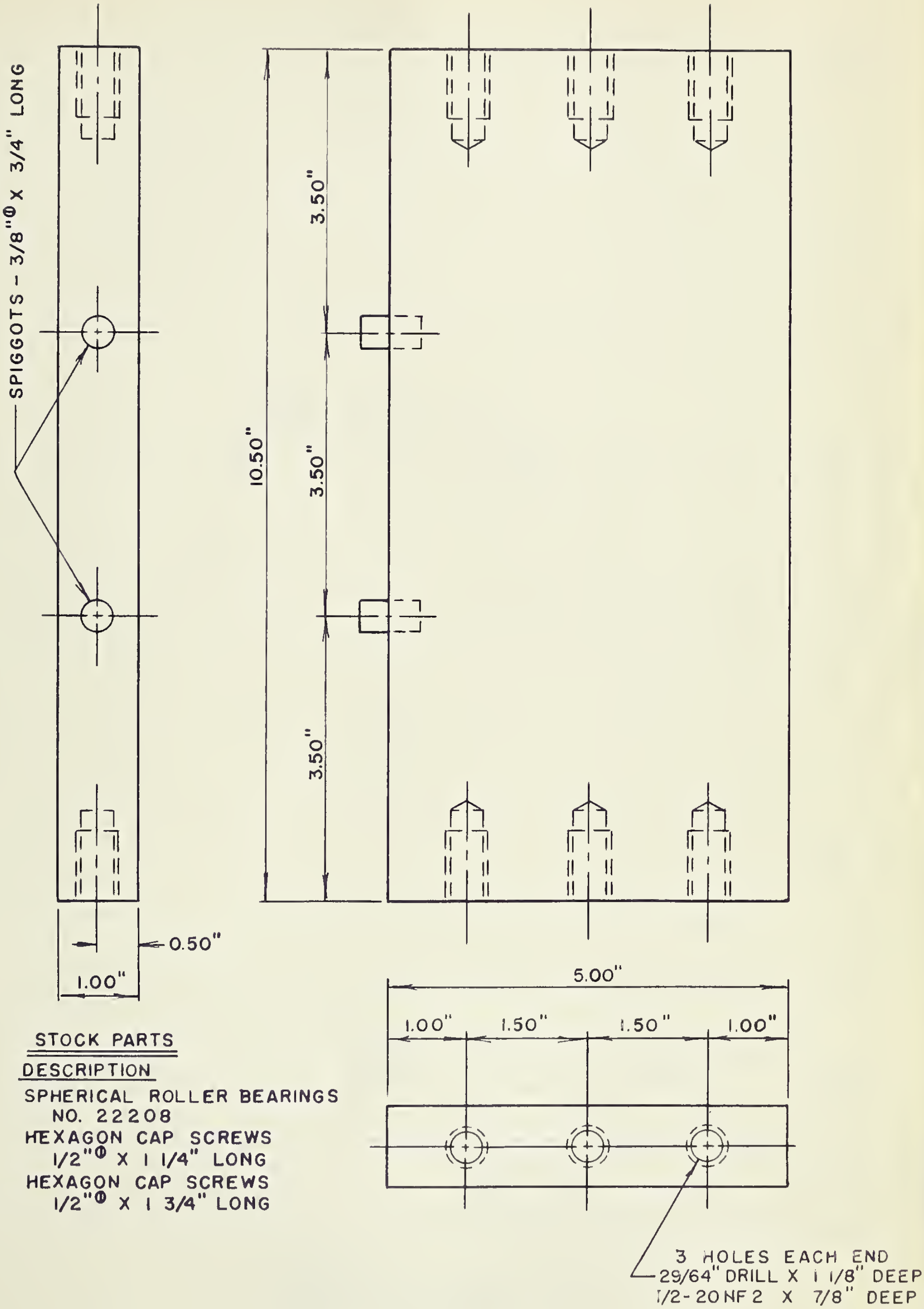


FIG. B4—DETAILS OF ROLLER MECHANISM

STIFFENER SECTION

1 REQUIRED
MATERIAL–COLD ROLLED STEEL
SIZE– 10 1/2" X 5" X 1"
SCALE–1/2 SIZE

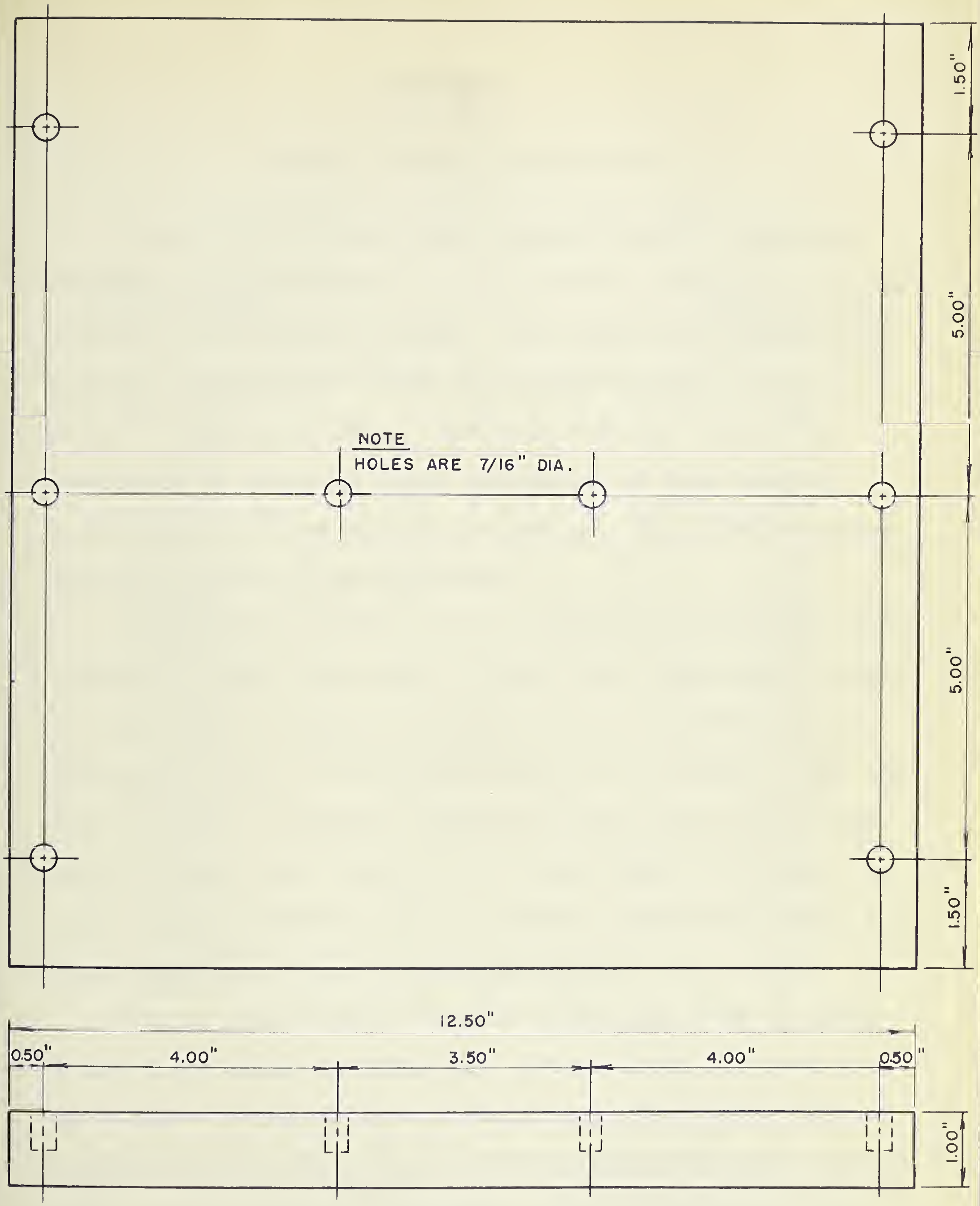


STOCK PARTS

NO. REQ'D.	DESCRIPTION
4	SPHERICAL ROLLER BEARINGS NO. 22208
12	HEXAGON CAP SCREWS 1/2"Φ X 1 1/4" LONG
6	HEXAGON CAP SCREWS 1/2"Φ X 1 3/4" LONG

FIG. B5–DETAILS OF ROLLER MECHANISM

TOP PLATE SECTION



1 REQUIRED
MATERIAL — HOT ROLLED PLATE
SIZE — 13" X 12.50" X 1"
SCALE — 1/2 SIZE

FIG. B6 — DETAILS OF ROLLER MECHANISM

APPENDIX C

DETAILS OF JACK CALIBRATION

Loads on the frames were measured with a Blackhawk pressure gauge designed for use with the hydraulic rams employed in the loading system. The gauge was calibrated by loading the hydraulic rams in a 200,000 pound capacity Baldwin Testing Machine. Load was applied to the test specimens in pressure gauge increments of four hundred pounds and the true loads were read on the Baldwin Testing Machine for each load increment.

Calibration figures for the double ram arrangement used in Tests 1 and 4 are shown in Table C1. Loads were applied to the frames in gauge increments of four hundred pounds throughout most of the loading range so in order to get the true load for a specific pressure gauge load it was necessary in most cases only to go to this table. In cases where gauge increments of two hundred pounds were used, the true loads were found by interpolation.

Calibration figures for the single ram used in Tests 2 and 3 are shown in Table C2. Actual loads for each pressure gauge increment were read directly from this table whenever possible and values were interpolated where necessary. Loads shown on the data sheets in Appendix F are actual loads in all cases.

TABLE C1

CALIBRATION FIGURES FOR DOUBLE RAMS

Blackhawk Pressure Gauge Reading Pounds	Actual Load on Each Hydraulic Ram Pounds
0	0
400	350
800	750
1200	1100
1600	1450
2000	1800
2400	2200
2800	2600
3200	3000
3600	3400
4000	3800
4400	4200
4800	4600
5200	5000
5600	5400
6000	5800
6400	6200
6800	6600
7200	7000
7600	7400
8000	7800
8400	8200
8800	8600
9200	9000
9600	9400
10000	9800

TABLE C2

CALIBRATION FIGURES FOR SINGLE RAM

Blackhawk Pressure Gauge Reading Pounds	Actual Load On Hydraulic Ram Pounds	Blackhawk Pressure Gauge Reading Pounds	Actual Load On Hydralic Ram Pounds
0	0	10000	9750
400	350	10400	10150
800	750	10800	10600
1200	1150	11200	11000
1600	1500	11600	11400
2000	1850	12000	11800
2400	2200	12400	12200
2800	2600	12800	12600
3200	3000	13200	13000
3600	3400	13600	13450
4000	3800	14000	13850
4400	4150	14400	14250
4800	4550	14800	14700
5200	4950	15200	15100
5600	5350	15600	15500
6000	5750	16000	15900
6400	6100	16400	16300
6800	6500	16800	16700
7200	6900	17200	17100
7600	7300	17600	17500
8000	7700	18000	17900
8400	8100	18400	18300
8800	8500	18800	18700
9200	8900	19200	19100
9600	9350	19600	19500
		20000	19950

APPENDIX D

CALCULATIONS

1. Ultimate Load Calculations

Calculations of the ultimate load for the three different loading conditions used in the tests are included in this section. All of the ultimate load calculations have been made using the "mechanism method" of analysis. This method will give a high value for the ultimate load if the incorrect mechanism is used in the analysis so in order to find the true ultimate load for a given structure all possible failure mechanisms must be analyzed. That mechanism forming at the lowest load will be the actual failure mechanism and should have a moment diagram that does not exceed the plastic moment at any section of the structure.

The calculations included in this section refer to the failure mechanism which gives the true ultimate load in each case. Moment diagrams for the true ultimate loads are shown to indicate that the plastic moment has not been exceeded at any section of the frames.

A. Frame Nos. 1 and 4

The loading on these frames is shown in Figure D1 (a). Possible plastic hinge locations are at sections 2, 3 and 4 for the combined loading. However, since the frame is indeterminate to the first degree it is necessary for plastic hinges to form at only two of the three possible

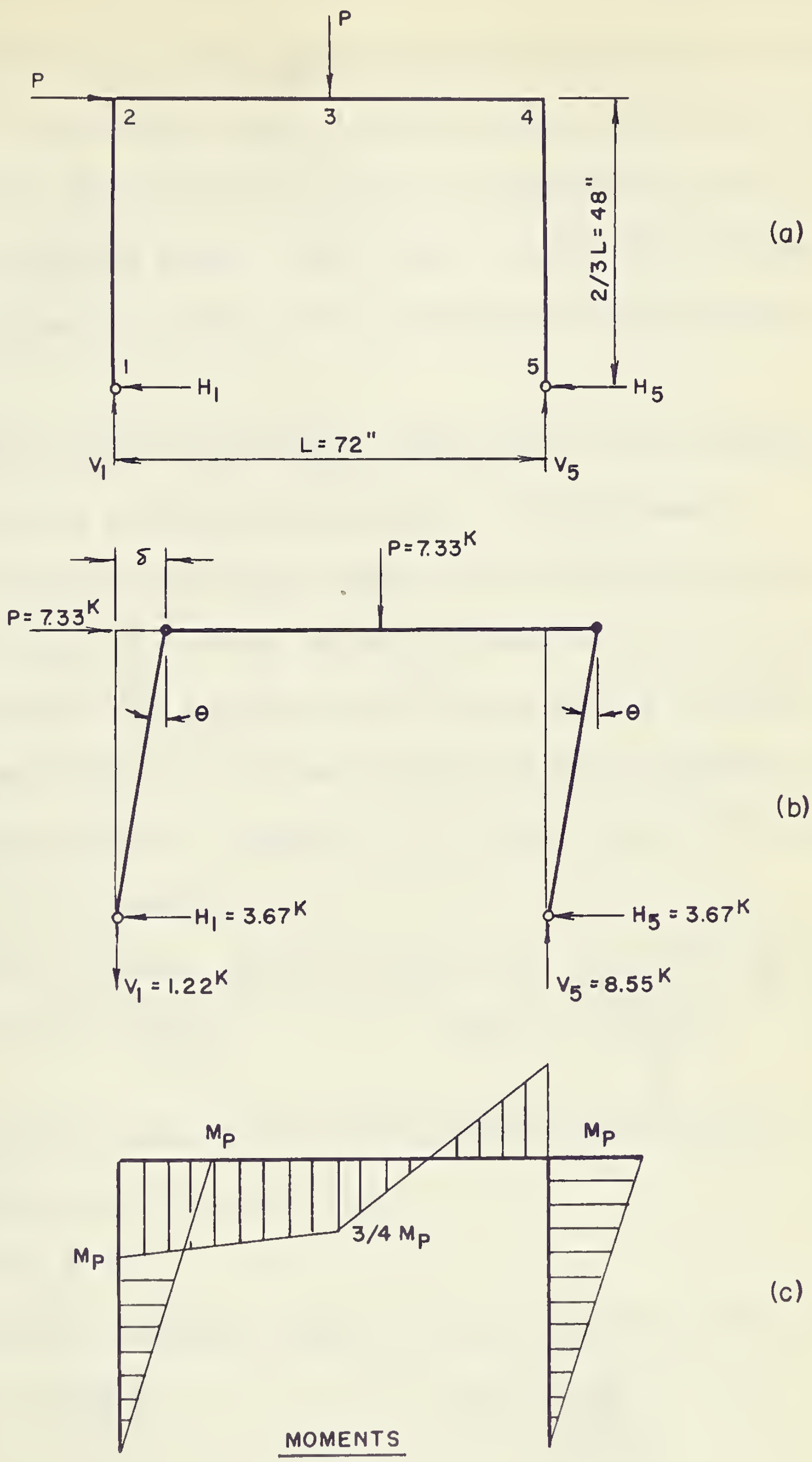


FIG. D1 — ULTIMATE LOAD ANALYSIS
FRAME NOS. 1 AND 4

locations. After analyzing the different possible failure mechanisms, it was found that the side-sway mechanism shown in Figure D1(b) with plastic hinges at sections 2 and 4 formed at the lowest load. Note that the plastic hinges have been assumed to form at the corners of the line diagram.

In Figure D1(b) the frame, loaded with the ultimate load P, has been given a virtual horizontal displacement . According to the theory of virtual work, the external work done by the applied loads in moving through their virtual displacements is equal to the internal work done by the plastic hinges as they rotate. The work done by each plastic hinge is equal to the plastic moment at the hinge times the angle through which it rotates.

The total external work in this case is given by:

$$W_e = P \times \delta = \frac{2PL\theta}{3} \qquad \text{since } \delta = \frac{2L\theta}{3}$$

Each plastic hinge has rotated through an angle θ so the total internal work is given by:

$$W_i = 2M_p\theta$$

Equating the external work to the internal work gives:

$$\frac{2PL\theta}{3} = 2M_p\theta \qquad \text{or } P = \frac{3M_p}{L}$$

$$M_p = \sigma_y \times Z$$

$\sigma_y = 44.0$ k.s.i. (from results of coupon tests)

Z for 4 I 9.5 = 4.0 in.^{3}

Therefore $M_p = 44.0 \times 4.0 = 176$ inch kips

$L = 72$ inches

Substituting these values into the equation for P gives:

$$P = \frac{3 \times 176}{72} = 7.33 \text{ kips}$$

Solving for reactions:

$$H_1 = H_5 = \frac{3M_p}{2L} = \frac{3 \times 176}{2 \times 72} = 3.67 \text{ kips}$$

$$M_1 = 48P + 36P - 72V_5 = 0$$

$$V_5 = \frac{84 \times 7.33}{72} = 8.55 \text{ kips}$$

$$M_5 = 48P - 36P + 72V_1 = 0$$

$$V_1 = -\frac{12 \times 7.33}{72} = -1.22 \text{ kips (acts downward)}$$

These reactions are shown on Figure D1(b)

The moment diagram for the ultimate load is shown in Figure D1(c). Moments are plotted on the tension side of the members.

$$M_2 = M_4 = M_p$$

$$M_3 = 48H_1 - 36V_1$$

$$= 48 \times 3.67 - 36 \times 1.22$$

$$= 176 - 44 = 132 \text{ inch-kips} = \tfrac{3}{4} M_p$$

It is therefore apparent that the plastic moment has not been exceeded at any point in the frames.

B. Frame No. 2

The loading on this frame is shown in Figure D2(a). There are only two possible plastic hinge locations,

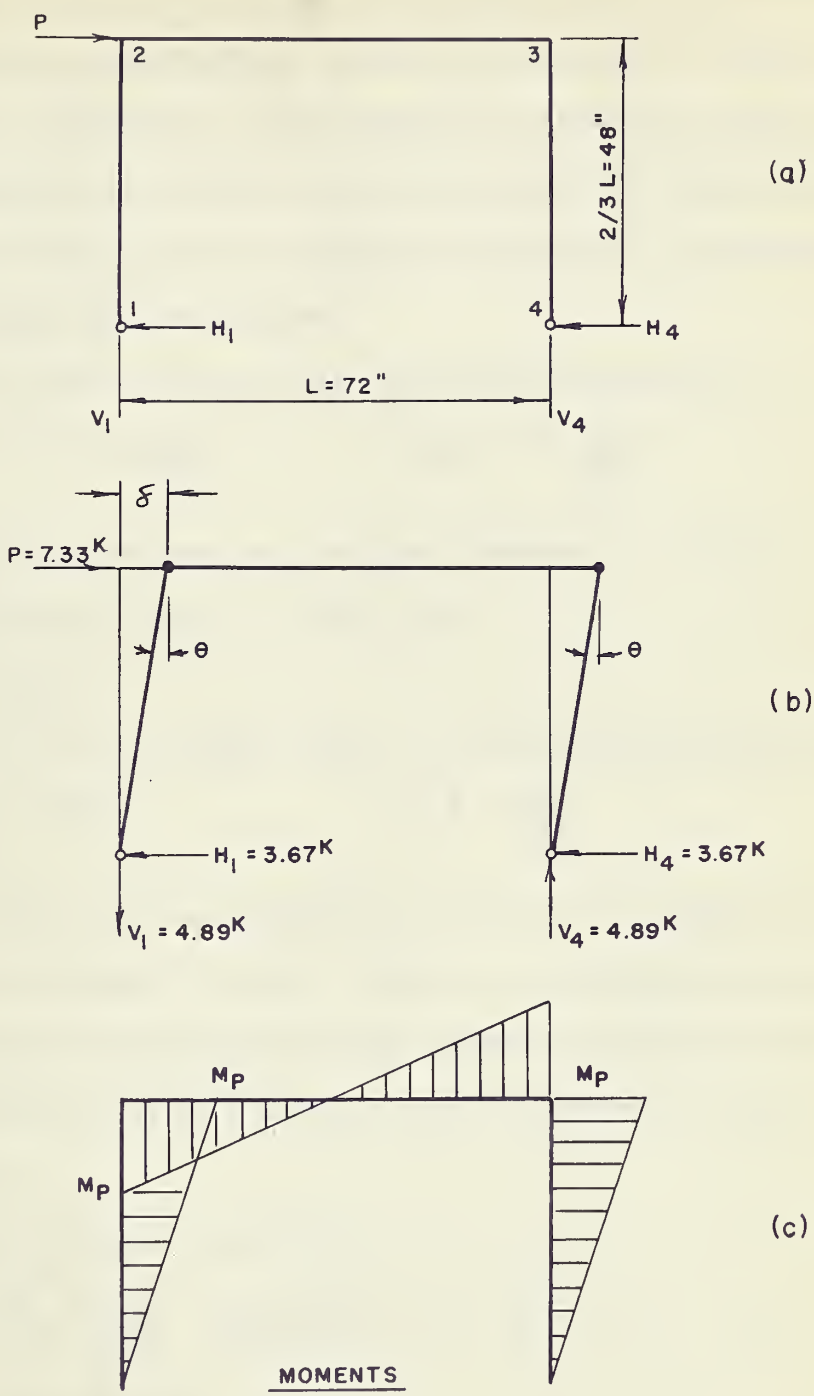


FIG. D2 — ULTIMATE LOAD ANALYSIS
FRAME NO. 2

at sections 2 and 3, and since two hinges are required to form the collapse mechanism, plastic hinges must form at both of these sections. The side-sway mechanism formed with plastic hinges at sections 2 and 3 is shown in Figure D2(b). The frame has been given a virtual horizontal displacement δ as indicated in the figure.

External work done by the horizontal load is:

$$W_e = P \times \delta = \frac{2PL\theta}{3} \qquad \text{since } \delta = \frac{2L\theta}{3}$$

Each plastic hinge has rotated through an angle θ so the total internal work is given by:

$$W_i = 2M_p\theta$$

Equating the external work to the internal work gives:

$$\frac{2PL\theta}{3} = 2M_p\theta \qquad \text{or } P = \frac{3M_p}{L}$$

This gives the same ultimate load of 7.33 kips as was found for frames 1 and 4. This is reasonable since side-sway mechanisms formed under both loading conditions and the horizontal reactions control the formation of this type of mechanism.

Solving for the reactions:

$$H_1 = H_4 = \frac{3M_p}{2L} = \frac{3 \times 176}{2 \times 72} = 3.67 \text{ kips}$$

$$M_1 = 48P - 72\, V_4 = 0$$

$$V_4 = \frac{48 \times 7.33}{72} = 4.89 \text{ kips}$$

$$V_1 = -\ 4.89 \text{ kips (acts downward)}$$

These reactions are shown on Figure D2(b).

The moment diagram for the ultimate load is shown in Figure D2(c). The plastic moment has not been exceeded at any section of the frame so the ultimate load determined must be the true ultimate load.

C. Frame No. 3

The loading on this frame is shown in Figure D3(a). Possible plastic hinge locations for this loading are at sections 2, 3 and 4. A beam mechanism is formed as shown in Figure D3(b) with plastic hinges at each of the three possible locations. A plastic hinge is formed at section 3 first and is followed by the simultaneous formation of plastic hinges at sections 2 and 4 due to the symmetrical loading. In Figure D3(b), the frame, subjected to the ultimate load P, has been given a virtual vertical displacement δ at the midspan of the beam.

External work done by the vertical load is:

$$W_e = P \times \delta = \frac{PL\theta}{2} \qquad \text{since } \delta = \frac{L\theta}{2}$$

The plastic hinges at the corners have each rotated through an angle θ and the hinge at the midspan of the beam through an angle 2θ as indicated in the figure. The total internal work then is:

$$W_i = 4M_p\theta$$

Equating the external work to the internal work gives:

$$\frac{PL\theta}{2} = 4M_p\theta \qquad \text{or } P = \frac{8M_p}{L} = \frac{8 \times 176}{72}$$

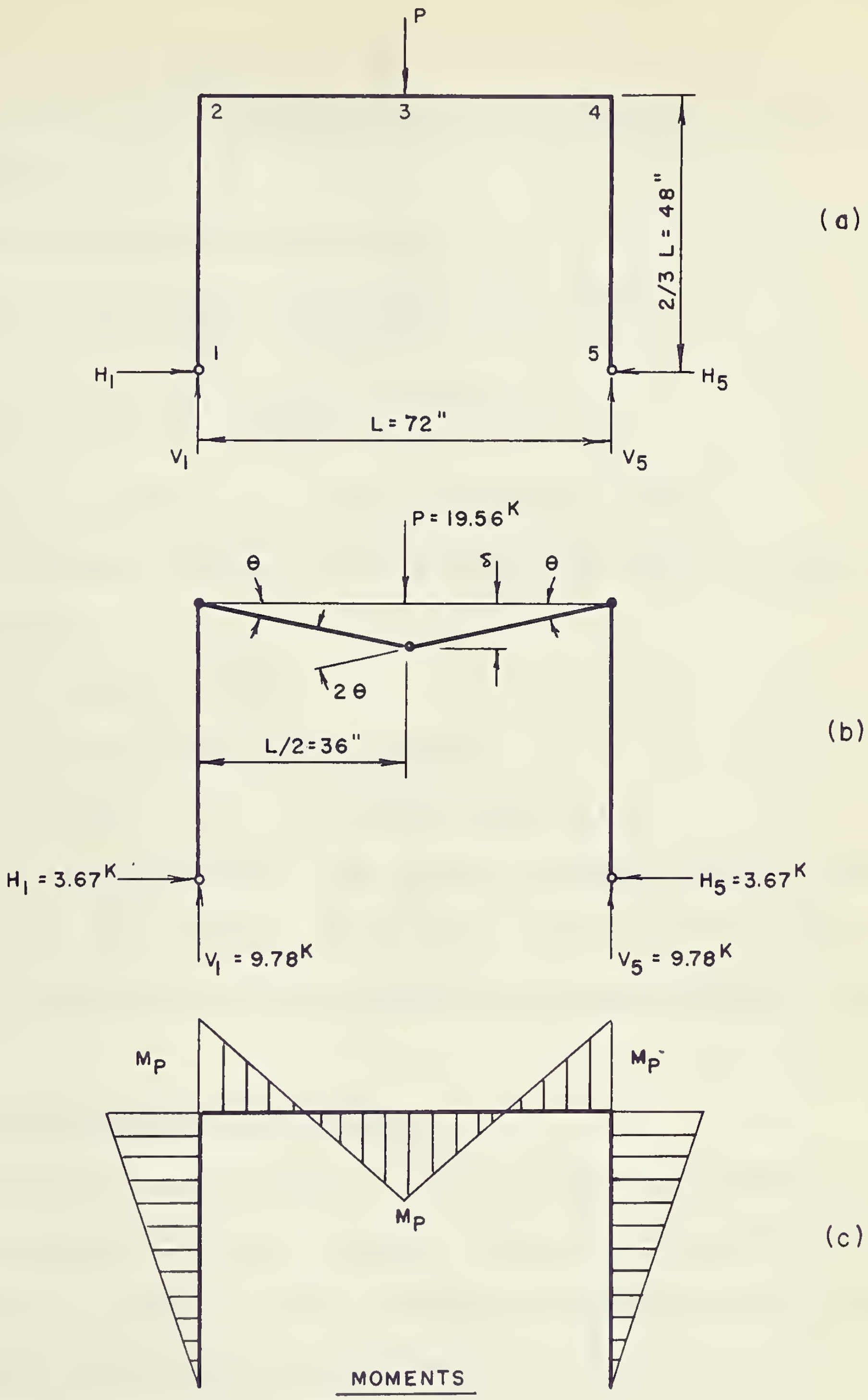


FIG. D3 — ULTIMATE LOAD ANALYSIS
FRAME NO. 3

$P = 19.56$ kips

The predicted ultimate load for frame No. 3 then is 19.56 kips.

Solving for the reactions:

$$H_1 = H_5 = \frac{3M_p}{2L} = \frac{3 \times 176}{2 \times 72} = 3.67 \text{ kips}$$

$$V_1 = V_5 = \frac{P}{2} = \frac{19.56}{2} = 9.78 \text{ kips}$$

These reactions are shown on Figure D3(b).

The moment diagram for the ultimate load is shown in Figure D3(c).

$$\begin{aligned} M_3 &= 36V_1 - 48H_1 \\ &= 36 \times 9.78 - 48 \times 3.67 \\ &= 352 - 176 = 176 \text{ inch kips} = M_p \end{aligned}$$

It is apparent that the plastic moment has not been exceeded at any section of the frame and that the full plastic moment acts at the predicted plastic hinge locations.

2. <u>Elastic Analysis of Frames</u>

Reactions and moments for the frames subjected to unit loads are shown in this section. These calculations are necessary in order to make subsequent theoretical deflection and moment-curvature calculations.

A. <u>Frame Nos. 1 and 4</u>

Figure D4(a) shows the moments and reactions calculated for the statically indeterminate frames loaded with unit horizontal and vertical loads as indicated. The statically indeterminate frame has been solved using the

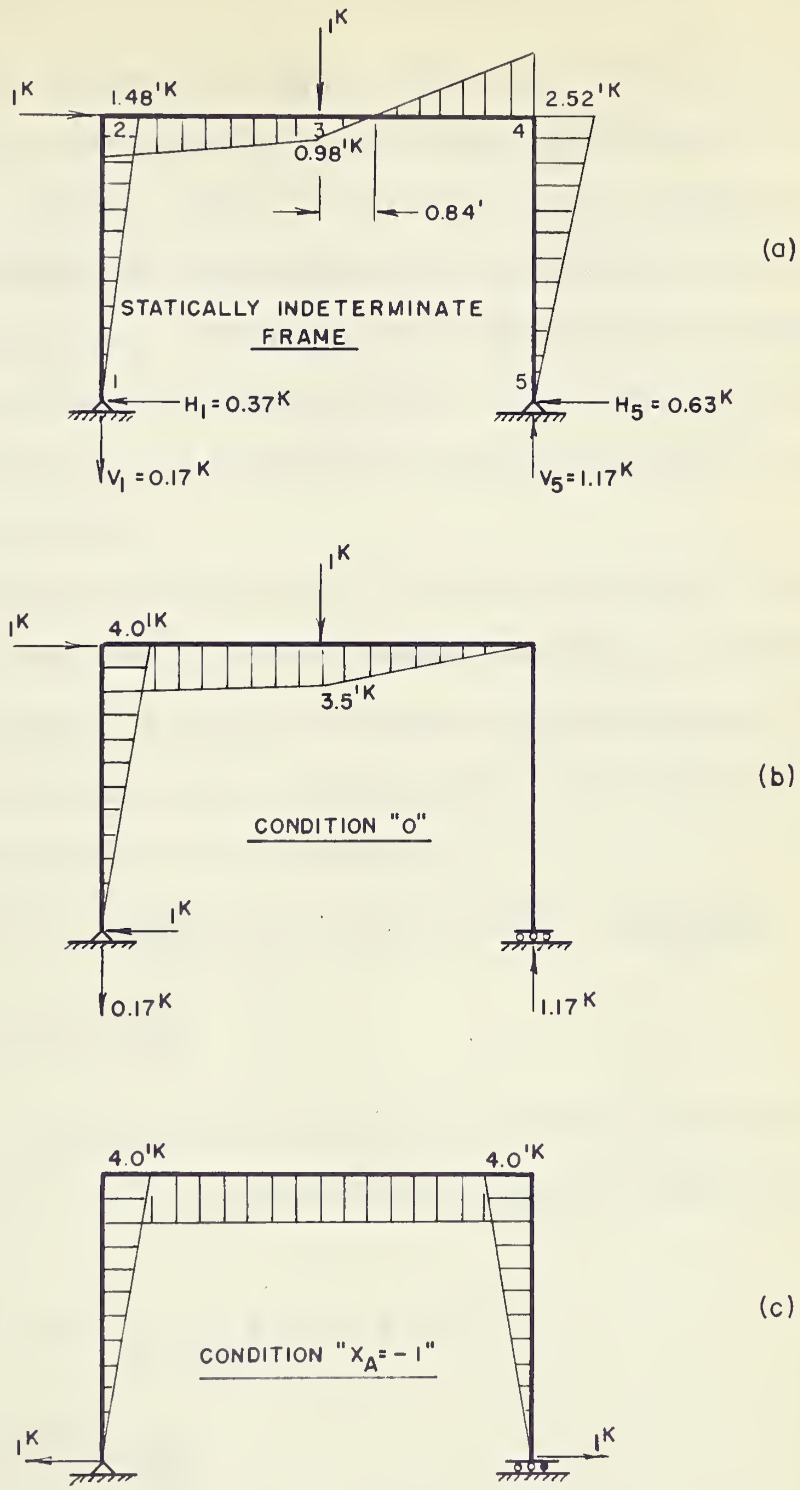


FIG. D4 — MOMENTS AND REACTIONS FOR UNIT LOADS FRAME NOS. 1 AND 4

Müller Breslau theory. In figure D4(b) the frame has been made statically determinate by replacing the hinge at section 5 with a roller. This is referred to as condition "O" and reactions and moments for this condition are indicated on the figure. Moments and reactions for condition "X_a = - 1" are shown in Figure D4(c). The loading for this condition consists of a horizontal unit load acting to the right at the roller.

The horizontal deflection (δ oa) at the roller for condition "O" can now be solved using the Müller Breslau tables. Beginning at the left column and proceeding clockwise around the frame, the solution for δoa using the Müller Breslau tables is as follows:

$$\delta_{oa} \text{ x EI} = \frac{4x4x4}{3} + \frac{3}{6}\,(4x12+3.5x12) + \frac{3x3.5x12}{6}$$

$$\delta_{oa} \text{ x EI} = \frac{262}{3}$$

δ_{aa}, the horizontal deflection at the roller for condition "X_a = - 1" is also solved using the Müller Breslau tables;

$$\delta_{aa} \text{ x EI} = \frac{2 \text{ x } 4 \text{ x } 16}{3} + 6 \text{ x } 16$$

$$\delta_{aa} \text{ x EI} = \frac{416}{3}$$

Knowing δ_{oa} and δ_{aa}, the horizontal reaction at section five of the indeterminate frame is determined as follows:

$$H5 = \frac{\delta_{oa}}{\delta_{aa}} = \frac{262 \text{ x } 3}{416 \text{ x } 3} = 0.63$$

With this value for H_5, the reactions and moments in the indeterminate frame are as shown in Figure D4(a).

B. Frame No. 2

Reactions and moments for frame No. 2 loaded with a unit horizontal load are shown in Figure D5. The indeterminate frame was solved using the Müller Breslau theory.

C. Frame No. 3

Reactions and moments for frame No. 3 loaded with a unit vertical load are shown in Figure D6. The indeterminate frame was again solved using the Müller Breslau theory. Calculations made for frames 2 and 3 were similar to those for frames 1 and 4 and for this reason it was felt not necessary to show them.

3. Deflection Calculations

A. Frame Nos. 1 and 4

Calculations for the horizontal deflection at the top of the windward column and for the vertical deflection at the midspan of the beam (both load points) are shown for frames 1 and 4. Referring to Figure D4(a), it can be seen that the largest bending moment for the unit loads acts at section 4. The magnitude of this moment is 2.52 foot kips or 30.2 inch kips. The first plastic hinge will therefore form at this section when the loads are equal to $\frac{176}{30.2} \times 1$ or 5.82 kips. 176 inch kips is the plastic moment for the

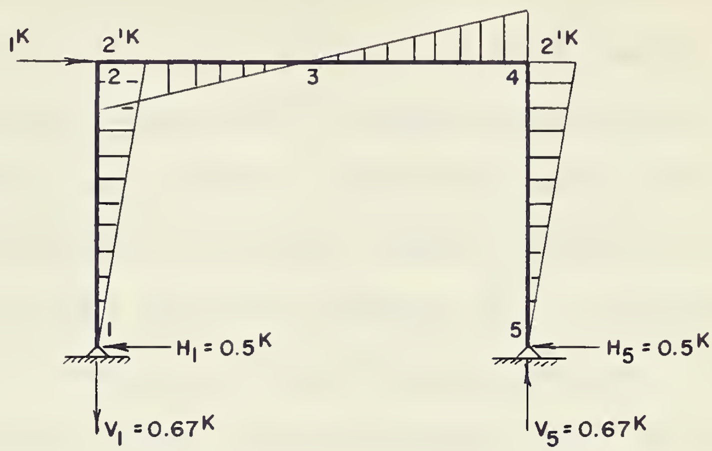


FIG. D5 — MOMENTS AND REACTIONS FOR UNIT LOAD
FRAME NO. 2

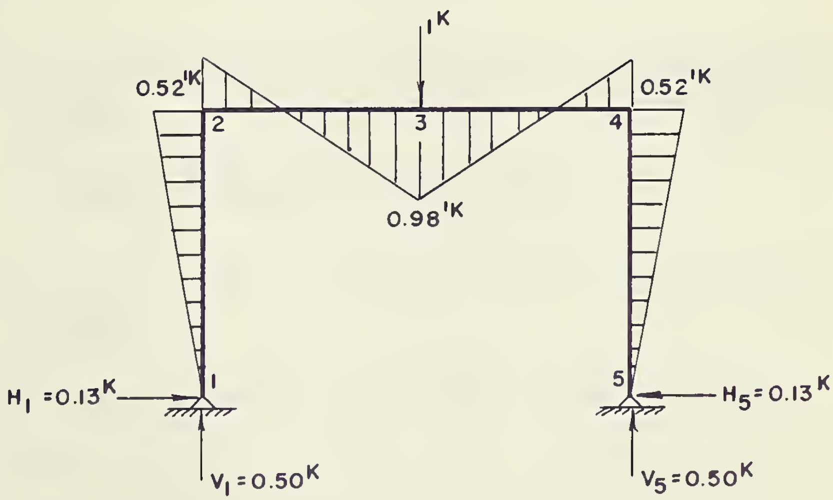


FIG. D6 — MOMENTS AND REACTIONS FOR UNIT LOAD
FRAME NO. 3

4 I 9.5 section.

Deflections prior to the formation of the first plastic hinge are calculated using the virtual work theory. The frame is shown in Figure D7(a) loaded with the 5.82 kips loads. Moments and reactions for this loading were determined by multiplying all values shown in Figure D4(a) by 5.82. Figure D7(b) shows the moments for a horizontal unit load applied at the top of the windward column. This diagram is the same as that shown in Figure D5. By equating the external work done by the unit load during the deflection of the frame in Figure D7(a) to the internal work done by the unit load moments during the same deflection, the following value for the horizontal deflection at the top of the windward column is obtained using Müller Breslau tables:

$$\frac{\delta_h \times EI}{1728} = \frac{4 \times 8.60 \times 2}{3} + \frac{3 \times 2 \times 22.9}{6} - \frac{0.84 \times 5.70 \times 0.56}{6}$$

$$+ \frac{2.16 \times 14.67 \times 4.56}{6} + \frac{4 \times 14.67 \times 2}{3}$$

$$\frac{\delta_h \times EI}{1728} = 22.9 + 22.9 - 0.4 + 24.1 + 39.1 = 108.6$$

$E = 31.0 \times 10^3$ k.s.i. (from coupon tests)

$I = 6.7$ in.^{4}

$$\delta_h = \frac{108.6 \times 1728}{6.7 \times 31.0 \times 10^3} = 0.903 \text{ inches}$$

The theoretical horizontal deflection at the top of the windward column when the first plastic hinge forms is then

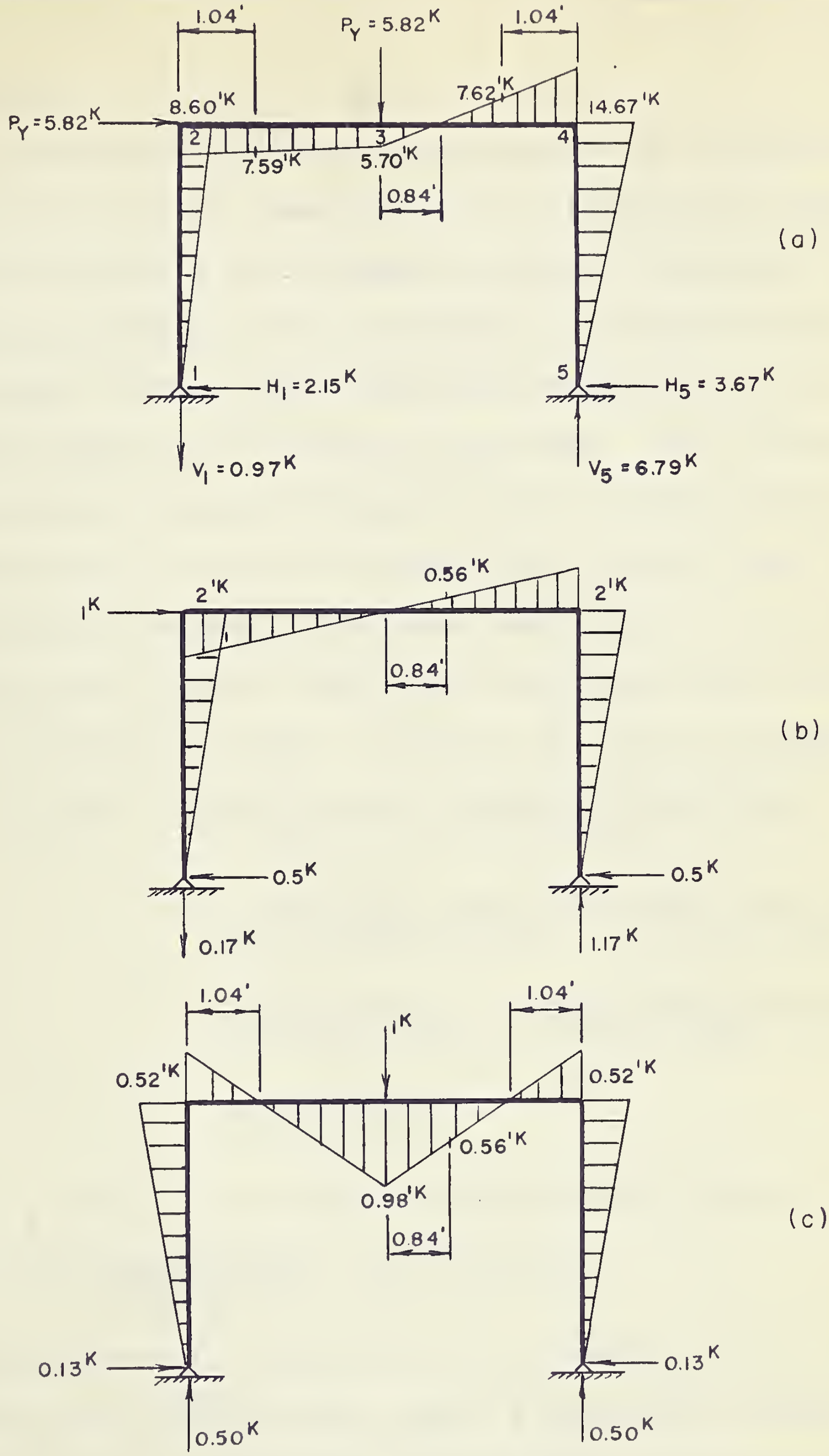


FIG. D7—DEFLECTION ANALYSIS
FRAME NOS. 1 AND 4

0.903 inches.

The theoretical vertical deflection at the midspan of the beam prior to the formation of the first plastic hinge is calculated in the same manner as above. The moment diagrams shown in Figures D7(a) and D7(c) are used in these calculations. Figure D7(c) shows the moments due to a unit load acting at the centre of the beam. This figure is the same as that shown in Figure D6. By equating the external work done by the unit load to the internal work done by the unit load moments during the deflection of the frame loaded with the 5.82 kip loads, the following value for the vertical deflection at the midspan of the beam is found:

$$\delta_v \times EI = \frac{-4\times8.60\times0.52}{3} - \frac{1.04\times0.52(17.20+7.59)}{6} + \frac{1.96\times0.98(11.40+7.50)}{6} + \frac{0.84\times5.70(1.96+0.56)}{6} - \frac{1.12\times0.56\times7.62}{6} + \frac{1.04\times0.52(29.34+7.62)}{6} + \frac{4\times14.67\times0.52}{3}$$

$$\delta_v \times EI = -5.96-2.24+6.08+2.01-0.80+3.34+10.17 = 12.60$$

$$\delta_v = \frac{12.60 \times 1728}{31.0\times10^3\times6.7} = 0.105 \text{ inches}$$

The theoretical deflection at the midspan of the beam when the first plastic hinge forms is then 0.105 inches.

Deflections at ultimate load have been calculated using the slope-deflection equations. Figure D8(a) shows the bend-

ing moments in the frame at ultimate load. These moments were determined in the ultimate load analysis (see Figure D1). A free-body diagram of the frames is shown in Figure D8(b).

The slope deflection equations necessary to solve for the horizontal and vertical deflections at ultimate load are as follows:

Note: Clockwise moment and angle change are considered positive.

$$\theta_{21} = \frac{3\delta_h}{2} + 0 + \frac{2L}{3x3EI}(-M_p - 0)$$

$$= \frac{3\delta_h}{2} - \frac{2M_pL}{9EI}$$

$$\theta_{23} = \frac{2\delta_v}{L} + 0 + \frac{L}{2x3EI}\left(M_p + \frac{3M_p}{8}\right)$$

$$= \frac{2\delta_v}{L} + \frac{11}{48}\frac{M_pL}{EI}$$

$$\theta_{32} = \frac{2\delta_v}{L} + 0 + \frac{L}{2x3EI}\left(\frac{-3M_p}{4} - \frac{M_p}{2}\right)$$

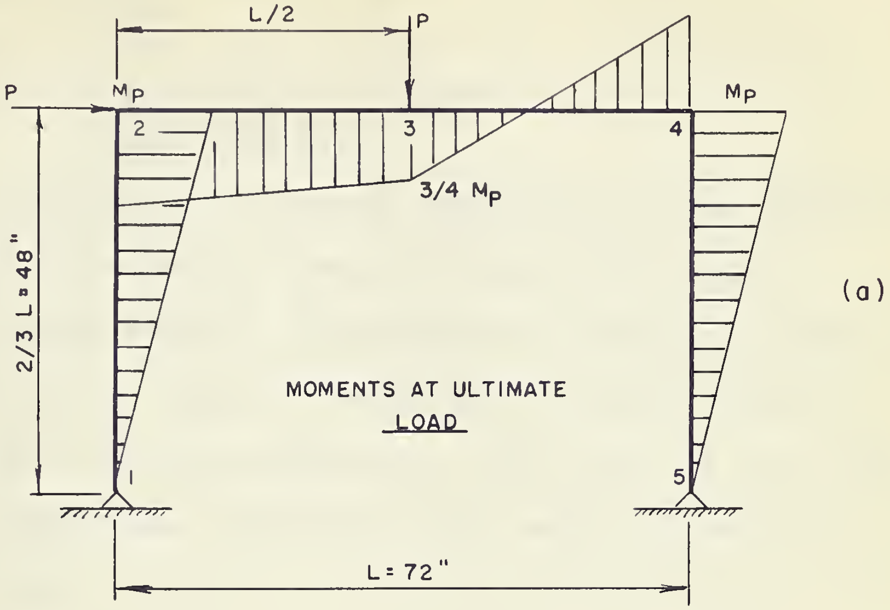
$$= \frac{2\delta_v}{L} - \frac{5}{24}\frac{M_pL}{3EI}$$

$$\theta_{34} = \frac{-2\delta_v}{L} + 0 + \frac{L}{2x3EI}\left(\frac{3M_p}{4} - \frac{M_p}{Z}\right)$$

$$= -\frac{2\delta_v}{L} + \frac{M_pL}{24EI}$$

No plastic hinge forms at section 3 so $\theta_{32} = \theta_{34}$

$$\frac{2\delta_v}{L} - \frac{5M_pL}{24EI} = \frac{2\delta_v}{L} + \frac{M_pL}{24EI}$$



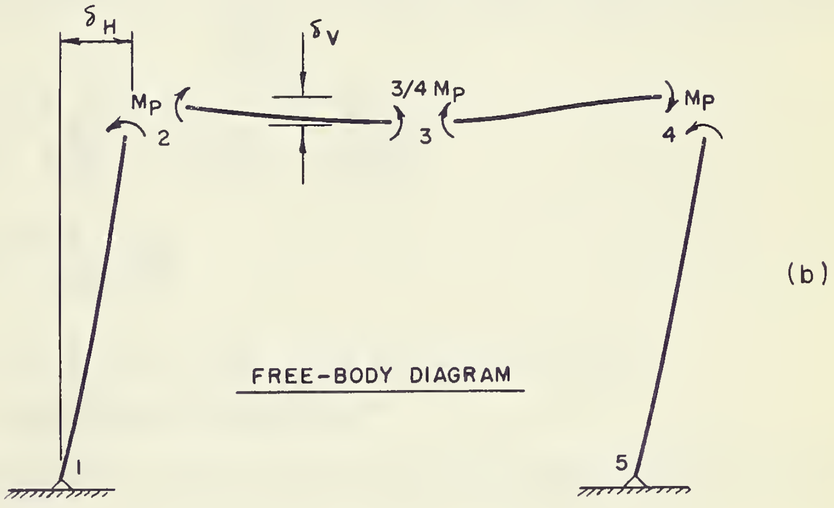


FIG. D8—DEFLECTION ANALYSIS
FRAME NOS. I AND 4

$$\delta_v = \frac{M_p L^2}{16EI}$$

$$\delta_v = \frac{176 \times 72 \times 72}{16 \times 31.0 \times 10^3 \times 6.7} = 0.274 \text{ inches}$$

The theoretical vertical deflection at the point when the collapse mechanism forms is then 0.274 inches.

It can be readily determined by looking at Figure D4(a) that the plastic hinge at section 2 is the last one to form in the collapse mechanism. Just prior to the formation of this hinge, continuity must exist at section 2 and $\theta_{21} = \theta_{23}$:

$$\frac{3\delta_h}{2L} - \frac{2LM_p}{9EI} = \frac{2\delta_v}{L} + \frac{11}{48}\frac{M_p L}{EI}$$

substituting $\delta_v = \dfrac{M_p L^2}{16EI}$ in the right hand side gives:

$$\frac{3\delta_h}{2L} = \frac{M_p L}{8EI} + \frac{11}{48}\frac{M_p L}{EI} + \frac{2M_p L}{9EI}$$

$$\frac{3\delta_h}{2L} = \frac{83}{144}\frac{M_p L}{EI}$$

$$\delta_h = \frac{2 \times 83 \times 176 \times 72 \times 72}{3 \times 144 \times 31.0 \times 10^3 \times 6.7} = 1.69 \text{ in.}$$

The horizontal deflection at the point when the collapse mechanism just forms is then 1.69 inches.

The values that have been calculated here were used in plotting the theoretical load-deflection curves for frame Nos. 1 and 4.

Frame No. 2

Both of the plastic hinges in the collapse mechanism for this frame form simultaneously when the ultimate load is reached. Consequently, there is only one break in the theoretical load-horizontal deflection curve as shown in Figure 31. The horizontal deflection at the point when the collapse mechanism has just formed (P = 7.33 kips) has been calculated to be 1.14 inches using the method of virtual work. Calculations are omitted here but the value may be checked with the aid of the moment diagram shown in Figure D5.

C. Frame No. 3

Figure D6 indicates that the first plastic hinge in this frame will form at the midspan of the beam since the largest bending moment (0.98 foot kips) for the unit loading acts at this section. The plastic hinge will form at this section at a predicted load of 14.95 kips if a value of 176 inch kips is used for the plastic moment value of the 4 I 9.5 section.

The vertical deflection at the midspan of the beam for the 14.95 kip load can be determined using the moment diagram shown in Figure D6. The moments for the 14.95 kip load are determined by multiplying the values shown in the figure by 14.95. Moment values for the unit load applied at the midspan of the beam are already given in the figure

and by equating the external work done by the unit load in moving through the deflection caused by the 14.95 kip load to the internal work done by the unit load moments during the same deflection, the vertical deflection for the 14.95 kip load is found to be 0.269 inches.

The theoretical vertical deflection of the midspan of the beam at the predicted ultimate load of 19.56 kips is calculated using the slope-deflection method. The moment diagram for the ultimate load is shown in Figure D9(a) along with a freebody diagram showing the frame at ultimate load in Figure D9(b). The slope-deflection equations necessary to solve for δ_v at ultimate load are as follows:

$$\theta_{21} = 0 + 0 + \frac{2L}{3x3EI}(+M_p)$$

$$= \frac{2M_pL}{9EI}$$

$$\theta_{23} = \frac{2\delta_v}{L} + 0 + \frac{L}{2x3EI}\left(-M_p + \frac{M_p}{2}\right)$$

$$= \frac{2\delta_v}{L} - \frac{M_pL}{12EI}$$

$$\theta_{43} = -\frac{2\delta_v}{L} + 0 + \frac{L}{2x3EI}\left(+M_p - \frac{M_p}{2}\right)$$

$$= -\frac{2\delta_v}{L} + \frac{M_pL}{12EI}$$

$$\theta_{45} = 0 + 0 + \frac{2L}{3x3EI}(-M_p)$$

$$= -\frac{2M_pL}{9EI}$$

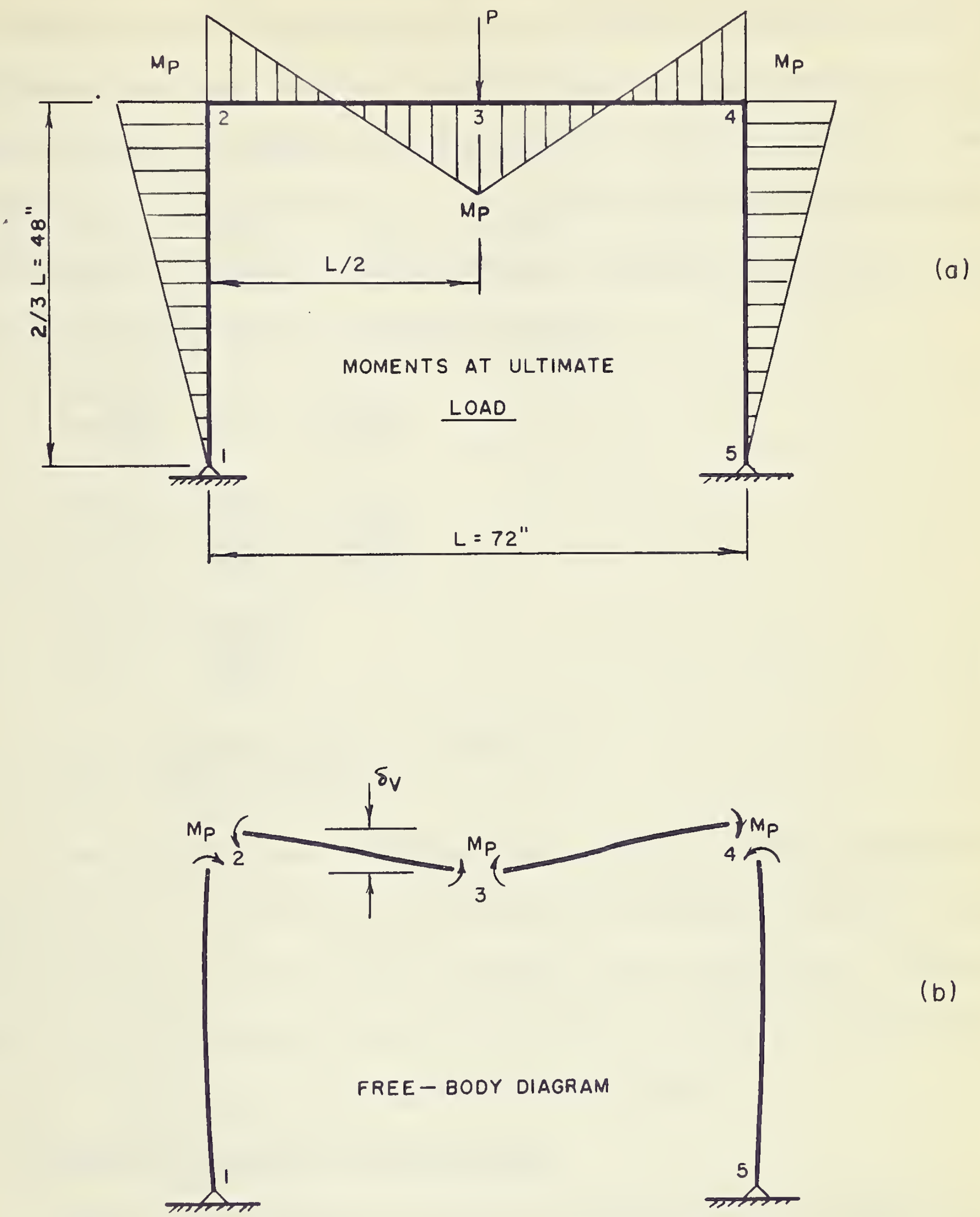


FIG. D9 — DEFLECTION ANALYSIS
FRAME NO. 3

Plastic hinges form simultaneously at sections 2 and 4 to complete the formation of the collapse mechanism when the ultimate load is reached. Just prior to the formation of these hinges, continuity must exist at both sections. Therefore, $\theta_{21} = \theta_{23}$ and $\theta_{34} = \theta_{45}$ just before the collapse mechanism is formed. Substituting appropriate values from the slope-deflection equations gives:

$$\frac{2M_pL}{9EI} = \frac{2\delta_v}{L} - \frac{M_pL}{12EI}$$

$$\frac{2\delta_v}{L} = \frac{8M_pL}{36EI} + \frac{3M_pL}{36EI}$$

$$\delta_v = \frac{11M_pL^2}{72EI}$$

$$\delta_v = \frac{11\text{x}176\text{x}72\text{x}72}{72\text{x}31\text{x}10^3\text{x}6.7} = 0.671 \text{ in.}$$

The theoretical vertical deflection at the midspan of the beam is therefore 0.671 inches at ultimate load. After the ultimate load has been reached, the deflection theoretically will increase with no increase in load as indicated by the theoretical load-deflection curves.

4. Moment-Curvature Calculations

Before the moment-curvature curves could be drawn it was necessary to establish a relationship between the load on the frames and the moment at the strain gauge locations near the top of each column. Curvatures were measured with the four flange gauges on each column (see Figure 9). They

were determined by taking the average strain for the four gauges at each load increment and dividing this value by one-half of the depth of the 4 I 9.5.

The first step in establishing the moment-load relationship was to determine the relationship between the load and the horizontal reactions at the base of each column. After the reactions were determined they were multiplied by the length of forty-four inches, the distance from the hinged column bases to the strain gauges (see Figure 9), which gave a value for the moment at the strain gauges for each load increment.

A. <u>Frame Nos. 1 and 4</u>

Previous calculations have shown that the first plastic hinge will form at the top of the leeward column of these frames at a predicted load of 5.82 kips. Prior to the formation of this plastic hinge the relationship between load and reactions is assumed to be that shown in Figure D4(a). Therefore, for loads less than 5.82 kips, the moment-load relationships are as follows:

Windward Column

Horizontal reaction for Load $P = 0.37P$ kips

Moment at strain gauges $= 0.37P \times 44 = 16.3P$ inch-kips.

Leeward Column

Horizontal reaction for load $P = 0.63P$ kips

Moment at strain gauges = $0.63P \times 44 = 27.7P$ inch-kips.

For loads in excess of 5.82 kips, the plastic hinge presumably has formed at the top of the leeward column and the horizontal reaction at the base of that column will remain constant at 0.63 x 5.82 or 3.67 kips. Any increase in horizontal load would then be taken by the horizontal reaction at the base of the leeward column. Therefore, for loads greater than 5.82 kips, the moment-load relationships are as follows:

Windward Column

Horizontal reaction for load P = $0.37 \times 5.82 + (P-5.82) = P-3.67$ kips

Moment at strain gauges = $44(P-3.67)$ inch kips

Leeward Column

Horizontal reaction = $0.63 \times 5.82 = 3.67$ kips (constant)

Moment = $27.7 \times 5.82 = 161.2$ inch-kips (constant)

Moment curvature values calculated for frame Nos. 1 and 4 are shown in Tables D1 and D2 respectively.

B. <u>Frame No. 2</u>

The horizontal reactions for this frame are both assumed to be equal to one-half of the applied load throughout the entire loading range. Therefore, the moment-load relationship for both columns is as follows:

TABLE D1 - MOMENT-CURVATURE VALUES

FRAME NO. 1

	Windward Column		Leeward Column	
Load Kips	Moment Inch-Kips	Curvature Rad./In. x 10^4	Moment Inch-Kips	Curvature Rad./In. x 10^4
0	0	0	0	0
0.35	5.7	0.27	9.7	0.51
0.75	12.2	0.61	20.8	1.10
1.10	17.9	0.86	30.5	1.53
1.45	23.6	1.18	40.2	2.17
1.80	29.3	1.42	49.9	2.78
2.20	35.8	1.81	60.9	3.55
2.60	41.4	2.17	72.0	4.27
3.00	48.9	2.75	83.1	5.21
3.40	55.4	3.41	94.2	6.16
3.80	61.9	4.25	105.3	7.16
4.20	68.4	4.84	116.3	8.33
4.60	74.9	5.59	127.4	10.00
5.00	81.5	6.55	138.5	11.77
5.40	88.0	7.58	149.6	13.90
5.80	94.5	9.48	160.7	18.20
6.20	111.6	12.15	161.2	25.59

TABLE D2 - MOMENT-CURVATURE VALUES

FRAME NO. 4

	Windward Column		Leeward Column	
Load Kips	Moment Inch-Kips	Curvature Rad./In. x 10^4	Moment Inch-Kips	Curvature Rad./In. x 10^4
0	0	0	0	0
0.35	5.7	0.19	9.7	0.39
0.75	12.2	0.47	20.8	0.89
1.10	17.9	0.77	30.5	1.41
1.45	23.6	1.07	40.2	1.91
1.80	29.3	1.39	49.9	2.45
2.20	35.8	1.74	60.9	3.07
2.60	41.4	2.06	72.0	3.80
3.00	48.9	2.39	83.1	4.49
3.40	55.4	2.76	94.2	5.25
3.80	61.9	3.05	105.3	6.14
4.20	68.4	3.33	116.3	6.92
4.60	74.9	3.76	127.4	8.24
5.00	81.5	4.14	138.5	9.44
5.40	88.0	4.60	149.6	11.10
5.80	94.5	5.44	160.7	13.09
6.20	111.6	6.50	161.2	19.11
6.60	129.2	7.83	161.2	30.83
7.00	146.8	10.64	161.2	47.19
7.40	161.5	13.31	161.2	69.97

Horizontal reaction for load P = P/2

Moment at strain gauges = 44 x P/2 = 22P

Moment-curvature values calculated for the frame are shown in Table D3.

C. Frame No. 3

Calculations made previously have shown that the first plastic hinge will form at the midspan of the beam at a predicted load of 14.95 kips. Prior to the formation of this hinge, the load-reaction relationship is assumed to be that shown in Figure D6. The frame is symmetrically loaded so the load-reaction relationships are the same for both columns. The relationship for loads less than 14.95 kips is as follows:

Horizontal reaction for load P = 0.13P kips

Moment at strain gauges = 0.13P x 44 = 5.72P inch-kips.

For loads greater than 14.95 kips, the plastic hinge is assumed to have formed at the midspan of the beam and a moment equal to the plastic moment for the 4 I 9.5 section (176 inch kips) is assumed to act there. Using this assumption, the following relationships are established for loads greater than 14.95 kips:

Horizontal reaction for load P = (0.375P-3.67) kips

Moment at strain gauges = 44(0.375P-3.67) inch-kips.

TABLE D3 - MOMENT-CURVATURE VALUES

FRAME NO. 2

Load Kips	Windward Column Moment Inch-Kips	Windward Column Curvature Rad./In. x 10^4	Leeward Column Moment Inch-Kips	Leeward Column Curvature Rad./In. x 10^4
0	0	0	0	0
0.35	7.7	0.31	7.7	0.30
0.75	16.5	0.74	16.5	0.75
1.15	25.3	1.15	25.3	1.17
1.50	33.0	1.52	33.0	1.57
1.85	40.7	1.89	40.7	2.01
2.20	48.4	2.25	48.4	2.43
2.60	57.2	2.67	57.2	2.80
3.00	66.0	3.04	66.0	3.24
3.40	74.8	3.52	74.8	3.64
3.80	83.6	4.13	83.6	3.96
4.15	91.3	4.85	91.3	4.31
4.55	100.1	5.93	100.1	4.71
4.95	108.9	7.09	108.9	5.16
5.35	117.7	8.63	117.7	5.61
5.75	126.5	11.06	126.5	6.20
6.10	134.2	14.45	134.2	7.43
6.50	143.0	22.17	143.0	10.31

TABLE D4 - MOMENT-CURVATURE VALUES

FRAME NO. 3

	Windward Column		Leeward Column	
Load Kips	Moment Inch-Kips	Curvature Rad./In. x 10^4	Moment Inch-Kips	Curvature Rad./In. x 10^4
0	0	0	0	0
0.75	4.3	0.13	4.3	0.23
1.50	8.6	0.35	8.6	0.45
2.20	12.6	0.55	12.6	0.67
3.00	17.2	0.79	17.2	0.89
3.80	21.7	1.02	21.7	1.12
4.55	26.0	1.25	26.0	1.35
5.35	30.6	1.47	30.6	1.58
6.10	34.9	1.68	34.9	1.81
6.90	39.5	1.91	39.5	2.05
7.70	44.0	2.13	44.0	2.29
8.50	48.6	2.36	48.6	2.52
9.35	53.5	2.62	53.5	2.77
10.15	58.0	2.87	58.0	3.01
11.00	62.9	3.13	62.9	3.28
11.80	67.5	3.41	67.5	3.55
12.60	72.1	3.73	72.1	3.86
13.45	77.0	4.12	77.0	4.25
14.25	81.5	4.65	81.5	4.69
15.10	88.0	5.38	88.0	5.23
15.90	101.2	6.31	101.2	5.89
16.70	114.3	7.57	114.3	6.64
17.50	127.5	8.98	127.5	7.33

Moment-curvature values calculated using these relationships are shown in Table D4.

D. <u>Theoretical Moment-Curvature Relationship for 4 I 9.5</u>

The idealized moment-curvature relationship for any structural steel section consists of two straight lines. Curvature is assumed to be proportional to the applied moment for moments less than the plastic moment capacity of the section and increases with no increase in moment when the plastic moment capacity is reached. Therefore, in order to draw the idealized moment-curvature curve for any section, it is necessary to calculate only the plastic moment capacity of the section and the curvature for that moment capacity.

The plastic moment for the 4 I 9.5 section used in these tests has previously been calculated as 176 inch kips. The section modulus for this section is 3.3 in.^{3} The theoretical curvature when the plastic moment capacity of the section has just been reached is then calculated as follows:

$$f_{max.} = \frac{M_p}{S} = \frac{176}{3.3} = 53.3 \text{ k.s.i.}$$

$$\epsilon = \frac{f}{E} = \frac{53.3}{31.0 \times 10^3} = 1.72 \times 10^{-3} \text{ in./in.}$$

$$\phi = \frac{\epsilon \times 2}{d} = \frac{1.72 \times 10^{-3} \times 2}{4} = 0.86 \times 10^{-3} \text{ radians per}$$

inch.

This curvature value was used to plot the idealized moment-curvature curve for the 4 I 9.5 section shown with the observed curves.

APPENDIX E

COUPON TEST DATA

Test data obtained from tests on four coupons taken from the web material of the 4 I 9.5 section are presented in this section. Coupons 1 and 2, which had two SR-4 strain gauges attached to them, were loaded in load increments of 500 pounds and strain gauge readings were taken at each load increment so the modulus of elasticity could be determined. Values of the yield load for the coupons were read directly from the load dial on the Baldwin Testing Machine. The yield stresses observed for coupons 1 and 2 are shown on the data sheets for these coupons.

Coupons 3 and 4 were loaded in the Baldwin Testing Machine at the A.S.T.M. specified maximum strain rate of 1/16 inch per minute per inch of gauge length to check the effect of loading rate on the value of yield stress obtained. Yield stresses observed at the higher strain rate were somewhat greater than those observed for the incremental loading used on coupons 1 and 2. Lower yield stresses of 50.7 k.s.i. and 52.0 k.s.i. were obtained at the higher strain rate as compared to 44.4 k.s.i. and 43.6 k.s.i. for the incremental loading.

COUPON TEST DATA

COUPON NO. 1

AVERAGE WIDTH 0.503 in. AVERAGE THICKNESS 0.309 in.

X-SECTIONAL AREA 0.155 sq. in.

LOAD LBS.	STRESS P.S.I.	SR-4 GAUGE NO. 1		SR-4 GAUGE NO. 2		AVERAGE STRAIN μ IN./IN.
		READING μ IN./IN.	STRAIN μ IN./IN.	READING μ IN./IN.	STRAIN μ IN./IN.	
0	0	8738	0	8247	0	0
500	3220	8884	146	8310	63	104.5
1000	6450	8982	244	8417	170	207.0
1500	9670	9084	346	8522	275	310.5
2000	12900	9187	449	8632	385	417.0
2500	16120	9290	552	8740	493	522.5
3000	19350	9391	653	8845	598	625.5
3500	22570	9495	757	8947	700	728.5
4000	25800	9598	860	9052	805	832.5
4500	29020	9702	964	9158	911	937.5
5000	32250	9800	1062	9263	1016	1039.0
5500	35470	9908	1170	9365	1118	1144.0
6000	38700	10017	1279	9474	1227	1253.0

UPPER YIELD STRESS 45.1 k.s.i. LOWER YIELD STRESS 44.4 k.s.i.

COUPON TEST DATA

COUPON NO. 2

AVERAGE WIDTH 0.504 in. AVERAGE THICKNESS 0.310 in.

X-SECTIONAL AREA 0.156 sq. in.

LOAD LBS.	STRESS P.S.I.	SR-4 GAUGE NO. 1		SR-4 GAUGE NO. 2		AVERAGE STRAIN μ IN./IN.
		READING μ IN./IN.	STRAIN μ IN./IN.	READING μ IN./IN.	STRAIN μ IN./IN.	
0	0	9377	0	9622	0	0
500	3200	9463	86	9622	100	93.0
1000	6410	9562	185	9830	208	196.5
1500	9610	9664	287	9439	317	302.0
2000	12820	9766	389	10056	434	411.5
2500	16020	9865	488	10161	539	513.5
3000	19230	9970	593	10265	643	618.0
3500	22430	10081	704	10371	749	726.5
4000	25640	10188	811	10472	850	830.5
4500	28840	10293	916	10577	955	935.5
5000	32050	10403	1026	10679	1057	1041.5
5500	35250	10511	1134	10787	1165	1149.5
6000	38460	10621	1244	10901	1279	1261.5

UPPER YIELD STRESS 44.3 k.s.i. LOWER YIELD STRESS 43.6 k.s.i.

APPENDIX F

TEST DATA

Test data are presented as follows:

1. Deflection data
2. SR-4 strain gauge data
3. Demec gauge data

Locations of the deflection instrumentation are as indicated below:

Dial No. 1 - Mounted at the top of the windward column or the column shown to the viewer's left in Figures 11, 12 and 13.

Scale No. 1 - Mounted at the same location as Dial No. 1 (See Figure 6).

Dial No. 2 - Mounted at midspan of the beam.

Scale No. 2 - Mounted at the same location as Dial No. 2 (See Figure 7).

Dial No. 3 - Mounted at the top of the leeward column or the column shown to the viewer's right in Figures 11, 12 and 13 (See Figure 8).

Dial No. 4 - Mounted on the roller plate to measure the horizontal movement of the roller mechanism.

Positive horizontal deflections indicate deflections in the direction of the applied horizontal loads or to the viewer's right in Figures 11, 12 and 13. Negative horizontal deflections are toward the viewer's left in these figures. Positive vertical deflections indicate deflections in the direction of the applied vertical load or upward when the frames are orientated as shown in Figures 11, 12 and 13.

SR-4 strain gauge locations are shown in Figure 9. Positive values indicate tensile strains, whereas negative values indicate compressive strains. This is also the case for the strains measured with the demec gauge. Demec No. 1 refers to the gauge points attached near the toe of the beam flange farthest away from the viewer in Figure 4 and demec No. 2 to the gauge points attached near the toe of the beam flange closest to the viewer in this figure.

DEFLECTION DATA

FRAME NO. 1

DATE Feb. 21, 1961

LOAD LBS.	0		350		750		1100		1450		1800	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	1.000	0.000	0.942	+0.058	0.875	+0.125	0.827	+0.173	0.763	+0.237	0.708	+0.292
SCALE NO. 1	11.000	0.000	10.940	+0.060	10.875	+0.125	10.825	+0.175	10.760	+0.240	10.705	+0.295
DIAL NO. 2												
SCALE NO. 2	2.080	0.000	2.095	+0.015	2.105	+0.025	2.110	+0.030	2.115	+0.035	2.120	+0.040
DIAL NO. 3												
DIAL NO. 4	0.000	0.000	0.030	+0.030	0.077	+0.077	0.111	+0.111	0.150	+0.150	0.187	+0.187

LOAD LBS.	2200		2600		3000		3400		3800		4200	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.645	+0.355	0.591	+0.409	0.520	+0.480	0.452	+0.548	0.386	+0.614	0.325	+0.675
SCALE NO. 1	10.645	+0.355	10.590	+0.410	10.520	+0.480	10.450	+0.550	10.385	+0.615	10.325	+0.675
DIAL NO. 2												
SCALE NO. 2	2.130	+0.050	2.140	+0.060	2.150	+0.070	2.160	+0.080	2.170	+0.090	2.180	+0.100
DIAL NO. 3												
DIAL NO. 4	0.232	+0.232	0.272	+0.272	0.327	+0.327	0.385	+0.385	0.447	+0.447	0.503	+0.503

DEFLECTION DATA

FRAME NO. 1

DATE Feb. 21, 1961

LOAD LBS.	4600		5000		5400		Reset Dial 1 5400		5600		5800	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.250	+0.750	0.169	+0.831	0.087	+0.913	0.907	+0.913	0.852	+0.968	0.759	+1.061
SCALE NO. 1	10.250	+0.750	10.170	+0.830	10.085	+0.915	-	-	-	-	9.940	+1.060
DIAL NO. 2												
SCALE NO. 2	2.195	+0.115	2.210	+0.130	2.220	+0.140	-	-	-	-	2.250	+0.170
DIAL NO. 3												
DIAL NO. 4	0.577	+0.577	0.676	+0.676	0.753	+0.753	-	-	-	-	0.914	+0.914

LOAD LBS.	Reset Dial 4 5800		6000		6200		6400		6600		6800	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	-	-	0.689	+1.131	0.547	+1.273	0.417	+1.403	0.237	+1.583	-	
SCALE NO. 1	-	-	-	-	9.730	+1.270	9.600	+1.400	9.420	+1.580	9.090	+1.910
DIAL NO. 2												
SCALE NO. 2	-	-	-	-	2.290	+0.210	2.320	+0.240	2.360	+0.280	2.420	+0.340
DIAL NO. 3												
DIAL NO. 4	0.000	+0.914	-	-	0.229	+1.143	-	-	0.561	+1.475	-	-

DEFLECTION DATA

FRAME NO. 1

DATE Feb. 21, 1961

LOAD LBS.	7000		7000		Recovery							
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	-	-	-	-	-	-						
SCALE NO. 1	7.400	+3.600	6.280	+4.720	7.440	+3.560						
DIAL NO. 2												
SCALE NO. 2	2.730	+0.650	3.010	+0.930	2.730	+0.650						
DIAL NO. 3												
DIAL NO. 4	-	-	-	-	-	-						

LOAD LBS.												
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1												
SCALE NO. 1												
DIAL NO. 2												
SCALE NO. 2												
DIAL NO. 3												
DIAL NO. 4												

DEFLECTION DATA

FRAME NO. - 2

DATE Feb. 24, 1961

LOAD LBS.	0		350		750		1150		1500		1850	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	1.000	0.000	0.958	+0.042	0.893	+0.107	0.835	+0.165	0.776	0.224	0.714	+0.286
SCALE NO. 1	11.50	0.00	11.46	+0.04	11.39	+0.11	11.34	+0.16	11.28	+0.22	11.22	+0.28
DIAL NO. 2												
SCALE NO. 2	9.67	0.00	9.67	0.00	9.67	0.00	9.67	0.00	9.67	0.00	9.67	0.00
DIAL NO. 3												
DIAL NO. 4	0.920	0.000	0.880	+0.040	0.823	+0.097	0.759	+0.161	0.704	+0.216	0.644	+0.276

LOAD LBS.	2200		2600		3000		3400		3800		4150	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.652	+0.348	0.597	+0.403	0.528	+0.472	0.465	+0.535	0.408	+0.592	0.350	+0.650
SCALE NO. 1	11.15	+0.35	11.10	+0.40	11.03	+0.47	10.97	+0.53	10.91	+0.59	10.85	+0.65
DIAL NO. 2												
SCALE NO. 2	9.67	0.00	9.67	0.00	9.67	0.00	9.66	+0.01	9.66	+0.01	9.66	+0.01
DIAL NO. 3												
DIAL NO. 4	0.585	+0.335	0.531	+0.389	+0.465	0.455	0.403	+0.517	0.348	+0.572	0.292	+0.628

DEFLECTION DATA

FRAME NO. - 2

DATE Feb. 24, 1961

LOAD LBS.	4550		4950		5350		Reset Dial 4 5350		5750		Reset Dial 1 5750	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.278	+0.722	0.205	+0.795	0.127	+0.873	–	–	0.038	+0.962	0.984	+0.962
SCALE NO. 1	10.78	+0.72	10.71	+0.79	10.63	+0.87	–	–	10.54	+0.96	–	–
DIAL NO. 2												
SCALE NO. 2	9.66	+0.01	9.65	+0.02	9.65	+0.02	–	–	9.65	+0.02	–	–
DIAL NO. 3												
DIAL NO. 4	0.222	+0.698	0.152	+0.768	0.077	+0.843	1.000	+0.843	0.924	+0.919	–	–

LOAD LBS.	5950		6100		6300		6500		6700		6900	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.932	+1.014	0.877	+1.069	0.813	+1.133	0.716	+1.230	0.566	+1.380	0.295	+1.651
SCALE NO. 1	10.48	+1.02	10.43	+1.07	10.37	+1.13	10.27	+1.23	10.12	+1.38	9.86	+1.64
DIAL NO. 2												
SCALE NO. 2	9.65	+0.02	9.65	+0.02	9.65	+0.02	9.64	+0.03	9.64	+0.03	9.62	+0.05
DIAL NO. 3												
DIAL NO. 4	0.863	+0.974	0.816	+1.027	0.754	+1.089	0.661	+1.182	0.517	+1.326	0.256	+1.587

DEFLECTION DATA

FRAME NO. - 2

DATE Feb. 24, 1961

LOAD LBS.	7100		Reset Dials 1 & 4 7100		7300		7500		Reset Dials 1 & 4 7500		7700	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.026	+1.220	0.956	1.220	0.610	+2.266	0.208	+2.662	0.936	+2.668	0.425	+3.179
SCALE NO. 1	9.59	+1.91	-	-	9.25	+2.25	8.85	+2.65	-	-	8.34	+3.16
DIAL NO. 2												
SCALE NO. 2	9.61	+0.06	-	-	9.59	+0.08	9.56	+0.11	-	-	9.52	+0.15
DIAL NO. 3												
DIAL NO. 4	0.096	+1.747	0.900	1.747	0.564	+2.083	0.170	+2.477	0.900	+2.477	0.398	+2.979

LOAD LBS.	7900		8300		8700		9350		Recovery			
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.111	+3.493	-	-	-	-	-	-	-	-		
SCALE NO. 1	8.02	+3.48	7.32	4.18	6.72	+4.78	5.85	+5.65	7.13	+4.37		
DIAL NO. 2												
SCALE NO. 2	9.50	+0.17	9.48	+0.19	9.42	+0.25	9.20	+0.47	9.35	+0.32		
DIAL NO. 3												
DIAL NO. 4	0.088	+3.289	-	-	-	-	-	-	-	-		

DEFLECTION DATA

FRAME NO. 3

DATE March 1, 1961

LOAD LBS.	0		750		1500		2200		3000		3800	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.660	0.000	0.663	0.003	0.665	-0.005	0.667	-0.007	0.669	-0.009	0.670	-0.010
SCALE NO. 1	6.000	0.000	6.005	-0.005	6.010	-0.010	6.015	-0.015	6.020	-0.020	6.020	-0.020
DIAL NO. 2	0.020	0.000	0.035	+0.015	0.050	+0.030	0.066	+0.046	0.083	+0.063	0.100	+0.080
SCALE NO. 2	8.680	0.000	8.660	+0.020	8.650	+0.030	8.630	+0.050	8.610	+0.070	8.590	+0.090
DIAL NO. 3	0.660	0.000	0.661	-0.001	0.661	-0.001	0.660	0.000	0.659	+0.001	0.658	+0.002
DIAL NO. 4												

LOAD LBS.	4550		5350		6100		6900		7700		8500	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.671	-0.011	0.673	-0.013	0.673	-0.013	0.674	-0.014	0.676	-0.016	0.678	-0.018
SCALE NO. 1	6.020	-0.020	6.020	-0.020	6.025	-0.025	6.025	-0.025	6.030	-0.030	6.030	-0.030
DIAL NO. 2	0.116	+0.096	0.133	+0.113	0.150	+0.130	0.167	+0.147	0.180	+0.160	0.192	+0.172
SCALE NO. 2	8.580	+0.100	8.560	+0.120	8.540	+0.140	8.520	+0.160	8.500	+0.180	8.470	+0.210
DIAL NO. 3	0.657	+0.003	0.655	+0.005	0.652	+0.008	0.649	+0.011	0.645	+0.015	0.642	+0.018
DIAL NO. 4												

DEFLECTION DATA

FRAME NO. 3

DATE March 1, 1961

LOAD LBS.	9350		10150		11000		11800		12600		13450	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.680	-0.020	0.681	-0.021	0.682	-0.022	0.683	-0.023	0.684	-0.024	0.686	-0.026
SCALE NO. 1	6.030	-0.030	6.035	-0.035	6.035	-0.035	6.040	-0.040	6.040	-0.040	6.045	-0.045
DIAL NO. 2	0.205	+0.185	0.223	+0.203	0.241	+0.221	0.260	+0.240	0.285	+0.265	0.315	+0.295
SCALE NO. 2	8.450	+0.230	8.425	+0.255	8.400	+0.280	8.375	+0.305	8.345	+0.335	8.305	+0.375
DIAL NO. 3	0.640	+0.020	0.638	+0.022	0.636	+0.024	0.633	+0.027	0.631	+0.029	0.628	+0.032
DIAL NO. 4												

LOAD LBS.	14250		15100		15900		16700		Reset Dial 2 16700		17500	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.689	-0.029	0.693	-0.033	0.697	-0.037	0.703	-0.043		-	0.703	-0.043
SCALE NO. 1	6.050	-0.050	6.055	-0.055	6.060	-0.060	6.070	-0.070	-	-	6.075	-0.075
DIAL NO. 2	0.357	+0.337	0.413	+0.393	0.470	+0.450	0.535	+0.515	0.072	+0.515	0.145	+0.581
SCALE NO. 2	8.260	+0.420	8.200	+0.480	8.135	+0.545	8.060	+0.620	-	-	7.990	+0.690
DIAL NO. 3	0.625	+0.035	0.622	+0.038	0.621	+0.039	0.620	+0.040	-	-	0.619	+0.041
DIAL NO. 4												

DEFLECTION DATA

FRAME NO. - 3

DATE March 1, 1961

LOAD LBS.	18300		19100		19950		20800		21000		Recovery	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.716	-0.056	0.726	-0.066	0.740	-0.080	0.772	-0.112	0.792	-0.132	0.768	-0.108
SCALE NO. 1	6.080	-0.080	6.095	-0.095	6.110	-0.110	6.145	-0.145	6.170	-0.170	6.130	-0.130
DIAL NO. 2	0.222	+0.658	0.325	+0.761	0.469	+0.905	0.801	+1.237	-	-	-	-
SCALE NO. 2	7.900	+0.730	7.790	+0.890	7.630	+1.050	7.290	+1.390	7.000	+1.680	7.520	+1.160
DIAL NO. 3	0.619	+0.041	0.619	+0.041	0.617	+0.043	0.612	+0.048	0.597	+0.063	0.631	+0.029
DIAL NO. 4												

LOAD LBS.												
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1												
SCALE NO. 1												
DIAL NO. 2												
SCALE NO. 2												
DIAL NO. 3												
DIAL NO. 4												

DEFLECTION DATA

FRAME NO. 4

DATE March 4, 1961

LOAD LBS.	0		350		750		1100		1450		1800	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	1.000	0.000	0.960	+0.040	0.906	+0.094	0.850	+0.150	0.792	+0.208	0.730	+0.270
SCALE NO. 1	9.000	0.000	8.955	+0.045	8.890	+0.110	8.850	+0.150	8.790	+0.210	8.730	+0.270
DIAL NO. 2												
SCALE NO. 2	8.700	0.000	8.690	+0.010	8.685	+0.015	8.675	+0.025	8.670	+0.030	8.660	+0.040
DIAL NO. 3	0.982	0.000	0.941	+0.041	0.866	+0.096	0.829	+0.153	0.770	+0.212	0.708	+0.274
DIAL NO. 4	0.020	0.000	0.040	+0.020	0.106	+0.086	0.173	+0.153	0.237	+0.217	0.305	+0.285

LOAD LBS.	2200		2600		3000		3400		3800		4200	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.663	+0.337	0.602	+0.398	0.536	+0.464	0.468	+0.532	0.401	+0.599	0.353	-0.647
SCALE NO. 1	8.660	+0.340	8.600	+0.400	8.530	+0.470	8.465	+0.535	8.405	+0.595	8.350	+0.650
DIAL NO. 2												
SCALE NO. 2	8.650	+0.050	8.640	+0.060	8.630	+0.070	8.620	+0.080	8.610	+0.090	8.600	+0.100
DIAL NO. 3	0.639	+0.343	0.577	+0.405	0.511	+0.471	0.440	+0.542	0.380	+0.602	0.325	+0.657
DIAL NO. 4	0.373	+0.353	0.438	+0.418	0.502	+0.482	0.564	+0.544	0.611	+0.591	0.658	+0.638

DEFLECTION DATA

FRAME NO. - 4

DATE March 4, 1961

LOAD LBS.	4600		5000		5400		5800		Reset Dials 5800		6200	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.272	+0.728	0.205	+0.795	0.126	+0.874	0.040	+0.960	0.336	+0.960	0.224	+1.072
SCALE NO. 1	8.270	+0.730	8.200	+0.800	8.125	+0.875	8.040	+0.960	-	-	7.930	+1.070
DIAL NO. 2												
SCALE NO. 2	8.590	+0.110	8.575	+0.125	8.560	+0.140	8.545	+0.155	-	-	8.525	+0.175
DIAL NO. 3	0.240	+0.742	0.173	+0.809	0.092	+0.890	0.005	+0.977	0.955	+0.977	0.841	+1.031
DIAL NO. 4	0.728	+0.708	0.782	+0.762	0.857	+0.837	0.939	+0.919	$\bar{1}$.971	+0.919	0.033	+1.031

LOAD LBS.	6600		Reset Dial 1 6600		7000		7400		7700		Recovery	
	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.	INSTR. READING	DEFL'N. INS.
DIAL NO. 1	0.042	+1.254	0.250	+1.254	0.676	+1.537	-	-	-	-	-	-
SCALE NO. 1	7.750	+1.250	-	-	7.480	+1.520	6.610	+2.390	5.270	+3.730	6.420	+2.580
DIAL NO. 2												
SCALE NO. 2	8.480	+0.220	-	-	8.410	+0.290	8.230	+0.470	7.865	+0.835	8.135	+0.565
DIAL NO. 3	0.652	+1.280	-	-	0.348	+1.584	-	-	-	-	-	-
DIAL NO. 4	0.267	+1.215	-	-	-	-	-	-	-	-	-	-

SR-4 STRAIN GAUGE DATA

FRAME NO. 1

DATE Feb. 21, 1961

LOAD	0	350		750		1100		1450		1800		2200	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1	11732	11678	- 54	11621	- 111	11559	- 173	11498	- 234	11460	- 272	11380	- 352
2	10089	10031	- 58	9956	- 133	9901	- 188	9830	- 259	9778	- 311	9722	- 367
3	9977	10031	+ 54	10085	+ 108	10120	+ 143	10170	+ 193	10211	+ 234	10268	+ 291
4	11005	11059	+ 54	11141	+ 136	11188	+ 183	11265	+ 260	11325	+ 320	11443	+ 438
5	13000	12998	- 2	13002	+ 2	12988	- 12	12991	- 9	12981	- 19	12977	- 23
6	11843	11839	- 4	11831	- 12	11825	- 18	11822	- 21	11808	- 35	11802	- 41
7	9392	9368	- 24	9361	- 31	9360	- 32	9366	- 26	9385	- 7	9360	- 32
8	9485	9530	+ 45	9582	+ 97	9600	+ 115	9658	+ 173	9686	+ 201	9734	+ 249
11	12831	12928	+ 97	13050	+ 219	13130	+ 299	13291	+ 460	13472	+ 641	13751	+ 920
12	9477	9578	+ 101	9691	+ 214	9781	+ 304	9893	+ 416	10002	+ 525	10121	+ 644
13	9542	9424	- 118	9301	- 241	9208	- 334	9083	- 459	8980	- 562	8881	- 661
14	10348	10253	- 95	10145	- 203	10060	- 288	9946	- 402	9850	- 498	9731	- 617
15	8167	8154	- 13	8161	- 6	8162	- 5	8155	- 12	8150	- 17	8141	- 26
16	10985	10989	+ 4	10992	+ 7	10998	+ 13	11001	+ 16	11002	+ 17	11005	+ 20
17	8480	8481	+ 1	8479	- 1	8479	- 1	8481	+ 1	8479	- 1	8479	- 1
18	8209	8246	+ 37	8280	+ 71	8310	+ 101	8350	+ 141	8379	+ 170	8420	+ 211

SR-4 STRAIN GAUGE DATA

FRAME NO. 1

DATE Feb. 21, 1961

LOAD		2600		3000		3400		3800		4200		4600	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		11344	-388	11262	-470	11179	-553	11080	-652	11010	-722	10920	-812
2		9660	-429	9582	-507	9541	-548	9471	-618	9410	-679	9348	-741
3		10304	+327	10350	+373	10380	+403	10393	+416	10415	+438	10431	+454
4		11600	+595	11857	+852	12233	+1228	12719	+1714	13032	+2031	13469	+2464
5		12971	-29	12968	-32	12961	-39	12965	-35	12961	-39	12970	-30
6		11800	-43	11795	-48	11800	-43	11810	-33	11819	-24	11835	-8
7		9351	-41	9356	-36	9352	-40	9356	-36	9351	-41	9353	-39
8		9770	+285	9827	+342	9880	+395	9923	+438	9966	+481	10022	+537
11		13990	+1159	14310	+1479	14736	+1905	15232	+2401	15834	+3003	16770	+3939
12		10231	+754	10382	+905	10445	+968	10492	+1015	10576	+1099	10655	+1178
13		8760	-782	8621	-921	8492	-1050	8379	-1163	8265	-1277	8121	-1421
14		9628	-720	9489	-859	9345	-1003	9202	-1146	9063	-1285	8888	-1460
15		8131	-36	8151	-16	8190	+23	8240	+73				
16		11008	+23	11010	+25	11011	+26	11020	+35	11031	+46	11053	+68
17		8478	-2	8480	0	8479	-1	8479	-1	8478	-2	8478	-2
18		8452	+243	8498	+289	8537	+328	8579	+370	8613	+404	8660	+451

SR-4 STRAIN GAUGE DATA

FRAME NO. 1

DATE Feb. 21, 1961

LOAD		5000		5400		5800		6200					
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN./IN.	INSTR. READING	STRAIN μ IN./IN.	INSTR. READING	STRAIN μ IN./IN.	INSTR. READING	STRAIN μ IN./IN.	INSTR. READING	STRAIN μ IN./IN.	INSTR. READING	STRAIN μ IN./IN.
1		10810	- 922	10691	-1041	10510	-1222	10220	-1512				
2		9268	- 821	9191	- 898	9068	-1021	8901	-1188				
3		10459	+ 482	10480	+ 503	10490	+ 513	10580	+ 603				
4		14020	+3015	14625	+3620	15830	+4825	17420	+6415				
5		12975	- 25	12970	- 30	13000	0	13090	+ 90				
6		11860	+ 17	11890	+ 47	11950	+ 107	12072	+ 229				
7		9350	- 42	9351	- 41	9358	- 34	9381	- 11				
8		10081	+ 596	10152	+ 667	10301	+ 816	10570	+1085				
11		17668	+4837	18310	+5479	18678	+5847	19569	+6738				
12		10775	+1298	11240	+1763	13088	+3611	15760	+6283				
13		7232	-1610	7630	-1212	6292	-2550	5622	-3220				
14		8674	-1674	8379	-1969	7793	-2555	6820	-3528				
15													
16		11088	+ 103	11032	+ 47	10725	- 260	10168	- 817				
17		8476	- 4	8476	- 4	8478	- 2	8482	+ 2				
18		8705	+ 496	8752	+ 543	8850	+ 641	8991	+ 782				

SR-4 STRAIN GAUGE DATA

FRAME NO. 2

DATE Feb. 24, 1961

LOAD		350		750		1150		1500		1850		2200	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1	10281	10348	+ 67	10433	+152	10504	+ 223	10581	+ 300	10666	+ 385	10749	+ 468
2	10834	10898	+ 64	10989	+ 155	11071	+ 237	11158	+ 324	11241	+ 407	11327	+ 493
3	10621	10561	- 60	10470	- 151	10382	- 239	10302	- 319	10291	- 330	10159	- 462
4	9080	9024	- 56	8945	- 135	8862	- 218	8809	- 271	8750	- 330	8701	- 379
5	11651	11599	- 52	11612	- 39	11609	- 42	11619	- 32	11623	- 28	11627	- 24
6	11979	11976	- 3	11974	- 5	11971	- 8	11968	- 11	11965	- 14	11960	- 19
7	12470	12473	+ 3	12478	+ 8	12484	+ 14	12489	+ 19	12490	+ 20	12492	+ 22
8	10831	10841	+ 10	10837	+ 6	10834	+ 3	10834	+ 3	10831	+ 0	10829	+ 2
11	12164	12100	- 64	12002	- 162	11911	- 253	11828	- 336	11740	- 424	11653	- 511
12	11906	11847	- 59	11769	- 137	11689	- 217	11609	- 297	11524	- 382	11452	- 454
13	11556	11607	+ 51	11690	+ 134	11767	+ 211	11843	+ 287	11927	+ 371	12012	+ 456
14	10077	10142	+ 65	10246	+ 169	10329	+ 252	10416	+ 339	10509	+ 432	10601	+ 524
15	11427	11429	+ 2	11435	+ 8	11437	+ 10	11440	+ 13	11443	+ 16	11446	+ 19
16	12707	12710	3	12713	+ 6	12713	+ 6	12721	+ 14	12721	+ 14	12724	+ 17
17	11860	11860	0	11867	+ 7	11868	+ 8	11869	+ 9	11871	+ 11	11874	+ 14
18	11769	11774	+ 5	11780	+ 11	11786	+ 17	11790	+ 21	11798	+ 29	11801	+ 32

SR-4 STRAIN GAUGE DATA

FRAME NO. 2

DATE Feb. 24, 1961

LOAD		2600		3000		3400		3800		4150		4550	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		10824	+ 543	10923	+ 642	11016	+ 735	11115	+ 834	11209	+ 928	11327	+1046
2		11451	+ 617	11488	+ 654	11561	+ 727	11630	+ 796	11690	+ 856	11766	+ 932
3		10102	- 519	10055	- 566	10010	- 611	9972	- 649	9938	- 683	9899	- 722
4		8625	- 455	8508	- 572	8334	- 746	8052	-1028	7670	-1410	7032	-2048
5		11637	- 14	11643	- 8	11641	- 10	11649	- 2	11643	- 8	11655	4
6		11951	- 28	11933	- 46	11911	- 68	11892	- 87	11861	- 118	11824	- 155
7		12494	+ 24	12500	+ 30	12501	+ 31	12504	+ 34	12503	+ 33	12510	+ 40
8		10827	- 4	10822	- 9	10819	- 12	10817	- 14	10812	- 19	10807	- 24
11		11576	- 588	11495	- 669	11433	- 731	11388	- 776	11345	- 819	11281	- 883
12		11384	- 522	11301	- 605	11222	- 684	11159	- 747	11092	- 814	11019	- 887
13		12078	+ 522	12160	+ 604	12237	+ 681	12298	+ 742	12359	+ 803	12433	+ 877
14		10683	+ 606	10792	+ 715	10890	+ 813	10983	+ 906	11092	+1015	11201	+1124
15		11441	+ 14	11439	+ 12	11436	+ 9	11430	+ 3	11421	- 6	11405	- 22
16		12719	+ 12	12715	+ 8	12711	+ 4	12706	- 1	12701	- 6	12691	- 16
17		11877	+ 17	11878	+ 18	11881	+ 21	11880	+ 20	11882	+ 22	11881	+ 21
18		11801	+ 32	11811	+ 42	11814	+ 45	11815	+ 46	11815	+ 46	11819	+ 50

SR-4 STRAIN GAUGE DATA

FRAME NO. 2

DATE Feb. 24, 1961

LOAD		4950		5350		5750		6100		6500			
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		11448	+1167	11581	+1300	11724	+1443	11878	+1597	12164	+1883		
2		11830	+ 996	11939	+1105	12069	+1235	12308	+1474	13661	+2827		
3		9841	- 780	9744	- 877	8839	-1782	6981	-3640	2769	-7852		
4		6354	-2726	5461	-3619	4691	-4389	4233	-4847	3902	-5178		
5		11659	8	11632	- 19	11543	- 108	11352	- 222	10972	- 679		
6		11777	- 202	11699	- 280	11583	- 396	11419	- 560	11172	-807		
7		12514	+ 44	12520	+ 50	12514	+ 44	12515	+ 45	12512	+ 42		
8		10801	- 30	10798	- 33	10790	- 41	10787	- 44	10794	- 37		
11		11201	- 963	11125	-1039	11043	-1121	10851	-1313	10257	-1907		
12		10948	- 958	10868	-1038	10778	-1128	10379	-1527	9391	-2515		
13		12514	+ 958	12592	+1036	12704	+1148	12863	+1307	13129	+1573		
14		11327	+1250	11452	+1375	11636	+1559	11876	+1792	12331	+2254		
15		11375	- 52	11349	- 78	11329	- 98	11297	- 130	11244	- 183		
16		12671	- 36	12653	- 54	12631	- 76	12584	- 123	12519	- 188		
17		11887	+ 27	11889	+ 29	11890	+ 30	11889	+ 29	11889	+ 29		
18		11819	+50	11821	+ 52	11824	+ 55	11826	+ 57	11839	+ 70		

SR-4 STRAIN GAUGE DATA

FRAME NO. 3

DATE March 1, 1961

LOAD	0	750		1500		2200		3000		3800		4550	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1	9519	9542	+ 23	9582	+ 63	9620	+ 101	9664	+ 145	9709	+ 190	9747	+ 228
2	9834	9855	+ 21	9897	+ 63	9936	+ 102	9981	+ 147	10029	+ 195	10070	+ 236
3	9444	9417	- 27	9374	- 70	9333	- 111	9284	- 160	9249	- 195	9189	- 255
4	10518	10489	- 29	10437	- 81	10389	- 129	10337	- 181	10285	- 233	10236	- 282
5	7897	7897	0	7897	0	7897	0	7897	0	7897	0	7898	+ 1
6	10872	10869	- 3	10863	- 9	10860	- 12	10854	- 18	10851	- 21	10850	- 22
7	9520	9521	+ 1	9527	+ 7	9530	+ 10	9532	+ 12	9534	+ 14	9533	+ 13
8	10333	10406	+ 73	10489	+ 156	10571	+ 238	10659	+ 326	10741	+ 408	10827	+ 494
11	10009	10048	+ 39	10083	+ 74	10122	+ 113	10159	+ 150	10193	+ 184	10227	+ 218
12	10049	10094	+ 45	10138	+ 89	10182	+ 133	10226	+ 177	10270	+ 221	10319	+ 270
13	10940	10891	49	10842	- 98	10794	- 146	10745	- 195	10692	- 248	10635	- 305
14	10000	9948	- 52	9902	- 98	9856	- 144	9809	- 191	9760	- 240	9711	- 289
15	10766	10766	0	10766	0	10766	0	10765	- 1	10764	- 2	10769	+ 3
16	9155	9154	- 1	9154	- 1	9155	0	9156	+ 1	9160	+ 5	9163	+ 8
17	7946	7946	0	7949	+ 3	7952	+ 6	7954	+ 8	7956	+ 10	7957	+ 11
18	10432	10503	+ 71	10588	+ 156	10668	+ 236	10751	+ 319	10837	+ 405	10928	+ 496

SR-4 STRAIN GAUGE DATA

FRAME NO. 3

DATE March 1, 1961

LOAD		5350		6100		6900		7700		8500		9350	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		9784	+ 265	9823	+ 304	9862	+ 343	9901	+ 382	9946	+ 427	9994	+ 475
2		10107	+ 273	10148	+ 314	10188	+ 354	10227	+ 393	10263	+ 429	10311	+ 477
3		9136	− 308	9092	− 352	9048	− 396	9017	− 427	8988	− 456	8949	− 495
4		10190	− 328	10142	− 376	10087	− 431	10020	− 498	9939	− 579	9871	− 647
5		7903	+ 6	7908	+ 11	7912	+ 15	7919	+ 22	7926	+ 29	7933	+ 36
6		10852	− 20	10851	− 21	10854	− 18	10855	− 17	10854	− 18	10855	− 17
7		9531	+ 11	9530	+ 10	9538	+ 18	9548	+ 28	9553	+ 33	9561	+ 41
8		10918	+ 585	11019	+ 686	11148	+ 815	11322	+ 989	11535	+ 1202	11778	+ 1445
11		10256	+ 247	10293	+ 284	10329	+ 320	10367	+ 358	10404	+ 395	10445	+ 436
12		10363	+ 314	10411	+ 362	10462	+ 413	10510	+ 461	10549	+ 500	10600	+ 551
13		10573	− 362	10528	− 412	10478	− 462	10432	− 508	10391	− 549	10343	− 597
14		9660	− 340	9614	− 386	9553	− 447	9494	− 506	9430	− 570	9367	− 633
15		10776	+ 10	10782	+ 16	10785	+ 19	10792	+ 26	10798	+ 32	10804	+ 38
16		9171	+ 16	9179	+ 24	9184	+ 29	9191	+ 36	9196	+ 41	9201	+ 46
17		7957	+ 11	7959	+ 13	7967	+ 21	7978	+ 32	7981	+ 35	7983	+ 37
18		11013	+ 581	11110	+ 678	11242	+ 810	11387	+ 955	11548	+ 1116	11772	+ 1340

SR-4 STRAIN GAUGE DATA

FRAME NO. 3

DATE March 1, 1961

LOAD		10150		11000		11800		12600		13450		14250	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/N.
1		10045	+ 5[illegible]	10091	+ 572	10142	+ 623	10203	+ 684	10274	+ 755	10337	+ 868
2		10356	+ 522	10402	+ 568	10454	+ 620	10525	+ 691	10601	+ 767	10713	+ 879
3		8899	- 545	8852	- 592	8801	- 643	8743	- 701	8669	- 775	8578	- 866
4		9811	- 707	9748	- 770	9680	- 838	9609	- 909	9516	-1002	9410	-1108
5		7939	+ 42	7946	+ 49	7951	+ 54	7959	+ 62	7969	+ 72	7979	+ 82
6		10858	- 14	10859	- 13	10859	- 13	10860	- 12	10863	- 9	10867	- 5
7		9563	+ 43	9558	+ 38	9549	+ 29	9508	- 12	9459	- 61	9416	- 104
8		12084	+1751	10505	+2172	13013	+2680	13794	+3461	15001	+4668	16830	+6497
11		10483	+ 474	10526	+ 517	10569	+ 560	10621	+ 612	10689	+ 680	10771	+ 762
12		10649	+ 600	10701	+ 652	10756	+ 707	10819	+ 770	10891	+ 842	10981	+ 932
13		10290	- 650	10234	- 706	10170	- 770	10102	- 838	10019	- 921	9919	-1021
14		9313	- 687	9251	- 749	9198	- 802	9131	- 869	9047	- 953	8959	-1041
15		10809	+ 43	10814	+ 48	10821	+ 55	10830	+ 64	10841	+ 75	10855	+ 89
16		9207	+ 52	9214	+ 59	9221	+ 66	9232	+ 77	9244	+ 89	9259	+ 104
17		7976	+ 30	7952	+ 6	7914	- 32	7849	- 97	7733	- 213	7644	- 302
18		12100	+1668	12366	+1934	12699	+2267	13203	+2771	14182	+3750	15797	+5365

SR-4 STRAIN GAUGE DATA

FRAME NO. 3

DATE March 1, 1961

LOAD		15100		15900		16700		17500					
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		10539	+1020	10846	+1327	11283	+1764	11774	+2255				
2		10902	+1068	11081	+1247	11319	+1485	11636	+1802				
3		8465	- 979	8352	-1092	8198	-1246	8023	-1421				
4		9279	-1239	9139	-1379	8959	-1559	8814	-1704				
5		7991	+ 94	8011	+ 114	8021	+124	8000	+ 103				
6		10871	- 1	10874	+ 2	10870	- 2	10844	- 28				
7		9418	- 102	9452	- 68	9509	- 11	9681	+ 161				
8		19113	+8780	20839	+10506	22349	+12016	23622	+13289				
11		10864	+ 855	10984	+ 975	11118	+1109	11222	+1213				
12		11091	+1042	11244	+1195	11423	+1374	11584	+1535				
13		9798	-1142	9678	-1262	9529	-1411	9389	-1551				
14		8851	-1149	8723	-1277	8585	-1415	8438	-1562				
15		10864	+ 98	10882	+ 116	10899	+ 133	10894	+ 128				
16		9269	+ 114	9289	+ 134	9309	+ 154	9317	+ 162				
17		7659	- 287	7811	- 135	8033	+ 87	8247	+ 301				
18		18213	+7781	20428	+9996	22345	+11913	23606	+13174				

SR-4 STRAIN GAUGE DATA

FRAME NO. 4

DATE March 4, 1961

LOAD	0	350		750		1100		1450		1800		2200	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1	10675	10630	- 45	10569	- 106	10505	- 170	10441	- 234	10378	- 297	10309	- 366
2	10877	10840	- 37	10780	- 97	10720	- 157	10659	- 218	10588	- 289	10508	- 369
3	11841	11870	+ 29	11923	+ 82	11976	+ 135	12036	+ 195	12090	+ 249	12150	+ 309
4	13029	13070	+ 41	13123	+ 94	13181	+ 152	13239	+ 210	13304	+ 275	13379	+ 350
5	10318	10313	- 5	10312	- 6	10310	- 8	10309	- 9	10308	- 10	10302	- 16
6	9600	9599	- 1	9598	- 2	9592	- 8	9591	- 9	9589	- 11	9586	- 14
7	9708	9702	- 6	9700	- 8	9699	- 9	9692	- 16	9690	- 18	9689	- 19
8	10169	10210	+ 41	10250	+ 81	10291	+ 122	10336	+ 167	10380	+ 211	10425	+ 256
11	10777	10851	+ 74	10949	+ 172	11049	+ 272	11148	+ 371	11242	+ 465	11342	+ 565
12	10830	10909	+ 79	11007	+ 177	11109	+ 279	11209	+ 379	11311	+ 481	11459	+ 629
13	10401	10321	- 80	10224	- 177	10123	- 278	10020	- 381	9901	- 500	9780	- 621
14	8487	8405	- 82	8302	- 185	8192	- 295	8087	- 400	7969	- 518	7849	- 638
15	10458	10459	+ 1	10455	- 3	10458	0	10463	+ 5	10478	+ 20	10496	+ 38
16	10686	10690	+ 4	10699	+ 13	10709	+ 23	10720	+ 34	10742	+ 56	10770	+ 84
17	8337	8333	- 4	8331	- 6	8329	- 8	8328	- 9	8324	- 13	8321	- 16
18	8929	8961	+ 32	8992	+ 63	9029	+ 100	9060	+ 131	9091	+ 162	9125	+ 196

SR-4 STRAIN GAUGE DATA

FRAME NO. 4

DATE March 4, 1961

LOAD		2600		3000		3400		3800		4200		4600	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		10242	- 433	10170	- 505	10095	- 580	10031	- 644	9969	- 706	9876	- 799
2		10439	- 438	10369	- 508	10293	- 584	10230	- 647	10175	- 702	10030	- 787
3		12202	+ 361	12262	+ 421	12331	+ 490	12389	+ 548	12441	+ 600	12521	+ 680
4		13443	+ 414	13510	+ 481	13580	+ 551	13633	+ 604	13681	+ 652	13769	+ 740
5		10301	- 17	10299	- 19	10298	- 20	10292	- 26	10231	- 27	10230	- 28
6		9582	- 18	9580	- 20	9578	- 22	9577	- 23	9572	- 28	9571	- 29
7		9682	- 26	9680	- 28	9673	- 35	9672	- 36	9670	- 38	9662	- 46
8		10470	+ 301	10520	+ 351	10570	+ 401	10621	+ 452	10670	+ 501	10741	+ 572
11		11476	+ 609	11509	+ 732	11602	+ 825	11695	+ 918	11722	+1015	11937	+1160
12		11675	+ 845	11942	+1112	12279	+1449	12567	+1737	12872	+2042	13456	+2626
13		9662	- 733	9531	- 870	9492	- 909	9271	-1130	9157	-1242	8990	-1411
14		7731	- 756	7607	- 880	7471	-1016	7361	-1126	7249	-1238	7094	-1293
15		10512	+ 54	10530	+ 72	10551	+ 93	10571	+ 113	10585	+ 127	10598	+ 140
16		10800	+ 114	10830	+ 144	10862	+ 176	10890	+ 204	10918	+ 232	10950	+ 264
17		8320	- 17	8318	- 19	8312	- 25	8310	- 27	8307	- 30	8299	- 38
18		9162	+ 233	9202	+ 273	9241	+ 312	9279	+ 350	9319	+ 330	9370	+ 441

SR-4 STRAIN GAUGE DATA

FRAME NO. 4

DATE March 4, 1961

LOAD		5000		5400		5800		6200		6600		7000	
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		9800	- 875	9709	- 966	9608	-1067	9482	-1193	9280	-1395	9000	-1675
2		10023	- 854	9940	- 937	9859	-1018	9746	-1131	9569	-1308	9365	-1512
3		12589	+ 748	12666	+ 825	12871	+1030	13128	+1287	13412	+1571	13746	+1905
4		13362	+ 833	13978	+ 949	14269	+1240	14618	+1589	15020	+1991	16450	+3421
5		10291	- 27	10290	- 28	10300	- 18	10312	- 6	10359	+ 41	10424	+ 106
6		9571	- 29	9574	- 26	9590	- 10	9602	+ 2	9661	+ 61	9775	+ 175
7		9654	- 54	9648	- 60	9639	- 69	9628	- 80	9611	- 97	9590	- 118
8		10798	+ 629	10856	+ 687	10940	+ 771	11051	+ 882	9250	+ 919	11620	+1451
11		12162	+1385	12579	+1802	13601	+2824	15858	+5081	21806	+11029	27633	+16856
12		13948	+3118	14560	+3730	15117	+4287	15498	+4668	15681	+4851	16991	+6161
13		8862	-1539	8720	-1681	8610	-1791	8491	-1910	8021	-2380	5560	-4841
14		6974	-1513	6817	-1670	6520	-1967	4862	-3625	2086	-6401	-1409	-9896
15		10602	+ 144	10604	+ 146	10622	+ 164	10673	+ 215	10600	+ 142	10321	- 137
16		10972	+ 286	10990	+ 304	10992	+ 306	10947	+ 261	10605	- 81	10022	- 664
17		8289	- 48	8280	- 57	8268	- 69	8252	- 85	8230	- 107	8191	- 146
18		9410	+ 481	9454	+ 525	9512	+ 583	9580	+ 651	9685	+ 756	9820	+ 891

SR-4 STRAIN GAUGE DATA

FRAME NO. 4

DATE March 4, 1961

LOAD		7400											
GAUGE NO.	INSTR. READING	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.	INSTR. READING	STRAIN μ IN/IN.
1		8619	-2056										
2		9275	-1602										
3		13811	+1970										
4		18049	+5020										
5		10519	± 201										
6		9949	+ 349										
7		9552	- 156										
8		11927	+1758										
11		32152	+21375										
12		20651	+9821										
13		1100	-9301										
14		-6995	-15482										
15		9979	- 470										
16		9738	- 948										
17		8153	- 184										
18		9893	+ 964										

DEMEC GAUGE DATA

FRAME NO. 2

DATE Feb. 24, 1961

LOAD LBS.	0	350		750		1150		1500		1850		2200	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1	.1014	0.1013	-.0001	0.1013	-.0001	0.1013	-.0001	0.1012	-.0002	.1012	-.0002	0.1011	-.0003
DEMEC NO. 2	.1480	0.1480	0.0000	0.1480	0.0000	0.1481	+.0001	0.1481	+.0001	.1481	+.0001	0.1481	+.0001

LOAD LBS.		2600		3000		3400		3800		4150		4550	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.1011	-.0003	0.1011	-.0003	0.1011	-.0003	0.1011	-.0003	.1012	-.0002	0.1011	.0001
DEMEC NO. 2		0.1481	+.0001	0.1481	+.0001	0.1481	+.0001	0.1481	+.0001	.1481	+.0001	0.1481	+.0001

DEMEC GAUGE DATA

FRAME NO. 2

DATE Feb. 24, 1961

LOAD LBS.		4950		5350		5750		5950		6100		6300	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.1013	-.0001	0.1012	-.0002	0.1013	-.0001	0.1012	-.0002	.1014	0.0000	0.1013	-.0001
DEMEC NO. 2		0.1481	+.0001	0.1481	+.0001	0.1483	+.0003	0.1481	+.0001	.1480	0.0000	0.1479	-.0001

LOAD LBS.		6500		6700		6900		7100		7300		7500	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.1013	-.0001	0.1012	-.0002	0.1014	0.0000	0.1013	-.0001	.1015	+.0001	0.1015	+.0001
DEMEC NO. 2		0.1479	-.0001	0.1479	-.0001	0.1477	-.0003	0.1477	-.0003	.1478	-.0002	0.1478	-.0002

DEMEC GAUGE DATA

FRAME NO. 2

DATE Feb. 24, 1961

LOAD LBS.		7700		7900		8300		8700		9350		Recovery	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.1015	+.0001	.1015	+.0001	-	-	-	-	.1021	+.0007	.1018	+.0004
DEMEC NO. 2		0.1477	-.0003	.1477	-.0003	-	-	-	-	.1470	-.0010	.1478	-.0002

LOAD LBS.													
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1													
DEMEC NO. 2													

DEMEC GAUGE DATA

FRAME NO. 3

DATE March 1, 1961

LOAD LBS.	0	750		1500		2200		3000		3800		4550	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1	.0450	0.0458	+.0008	0.0467	+.0017	0.0476	+.0026	0.0484	+.0034	.0494	+.0044	0.0502	+.0052
DEMEC NO. 2	.0422	0.0430	+.0008	0.0438	+.0016	0.0447	+.0025	0.0456	+.0034	.0464	+.0042	0.0474	+.0052

LOAD LBS.		5350		6100		6900		7700		8500		9350	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.0511	.0061	0.0523	+.0073	0.0537	+.0087	0.0557	+.0107	0.0577	0.0127	0.0598	0.0148
DEMEC NO. 2		0.0483	+.0061	0.0492	+.0070	0.0498	+.0076	0.0502	+.0080	.0507	0.0085	0.0516	0.0094

DEMEC GAUGE DATA

FRAME NO. 3

DATE March 1, 1961

LOAD LBS.		10150		11000		11800		12600		13450		14250	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.0617	+.0167	0.0639	+.0189	0.0663	+.0213	0.0690	+.0240	.0727	+.0277	0.0780	+.0330
DEMEC NO. 2		0.0527	+.0105	0.0540	+.0118	0.0555	.0133	0.0583	+0161	.0639	+.0718	0.0718	+.0296

LOAD LBS.		15100		15900		16700		17500		18300		19100	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.0865	+.0415	0.0956	+.0506	0.1075	+.0625	0.1177	+.0727	.1306	+.0856	0.1465	+.1015
DEMEC NO. 2		0.0822	+.0400	0.0927	+.0505	0.1057	+.0635	0.1170	+.0748	.1311	+.0889	0.1481	+.1059

DEMEC GAUGE DATA

FRAME NO. 3

DATE March 1, 1961

LOAD LBS.		10950												
	INSTR. READING	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.
DEMEC NO. 1		0.1660	0.1216										
DEMEC NO. 2		0.1710	0.1238										

LOAD LBS.													
	INSTR. READING	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.	INSTR. READING	STRAIN IN/IN.
DEMEC NO. 1													
DEMEC NO. 2													

DEMEC GAUGE DATA

FRAME NO. 4

DATE March 4, 1961

LOAD LBS.	0	350		750		1100		1450		1800		2200	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1	.0448	0.0453	+.0005	0.0457	+.0009	0.0462	+.0014	0.0467	+.0012	.0471	+.0023	0.0476	+.0028
DEMEC NO. 2	.0461	0.0463	+.0002	0.0468	+.0007	0.0471	+.0010	0.0474	+.0013	.0477	+.0016	0.0480	+.0019
LOAD LBS.		2600		3000		3400		3800		4200		4600	
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.0481	+.0033	0.0482	+.0034	0.0492	+.0044	0.0497	+.0049	.0501	+.0053	0.0508	+.0060
DEMEC NO. 2		0.0484	+.0023	0.0488	+.0027	0.0494	+.0033	0.0497	+.0036	.0502	+.0041	0.0507	+.0046

DEMEC GAUGE DATA

FRAME NO. 4

DATE March 4, 1961

LOAD LBS.		5000		5400		5800		6200		6600		7000	
	INSTR. READING	INSTR READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		0.0514	+.0066	0.0521	+.0073	0.0529	+.0081	0.0539	+.0091	.0554	+.0106	0.0574	+.0126
DEMEC NO. 2		0.0511	+.0050	0.0517	+.0056	0.0522	+.0061	0.0530	+.0069	.0543	+.0082	0.0565	+.0104

LOAD LBS.		7400		7700		Recovery							
	INSTR. READING	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.	INSTR. READING	STRAIN IN./IN.
DEMEC NO. 1		–	–	–	–	0.0495	+.0047						
DEMEC NO. 2		–	–	–	–	.0524	+.0063						